The 11th Supernova Neutrino Workshop / 第11回 超新星ニュートリノ研究会

Komaba Campus, The University of Tokyo

March 3rd / 4th

Dissecting Diffuse Supernova Neutrino Background Flux over Wide Energy Range in Upcoming Era

次世代検出器における広いエネルギー範囲での超新星背景ニュートリノフラックス解析に向けた研究

ASHIDA, Yosuke / 芦田 洋輔

Tohoku University / 東北大学

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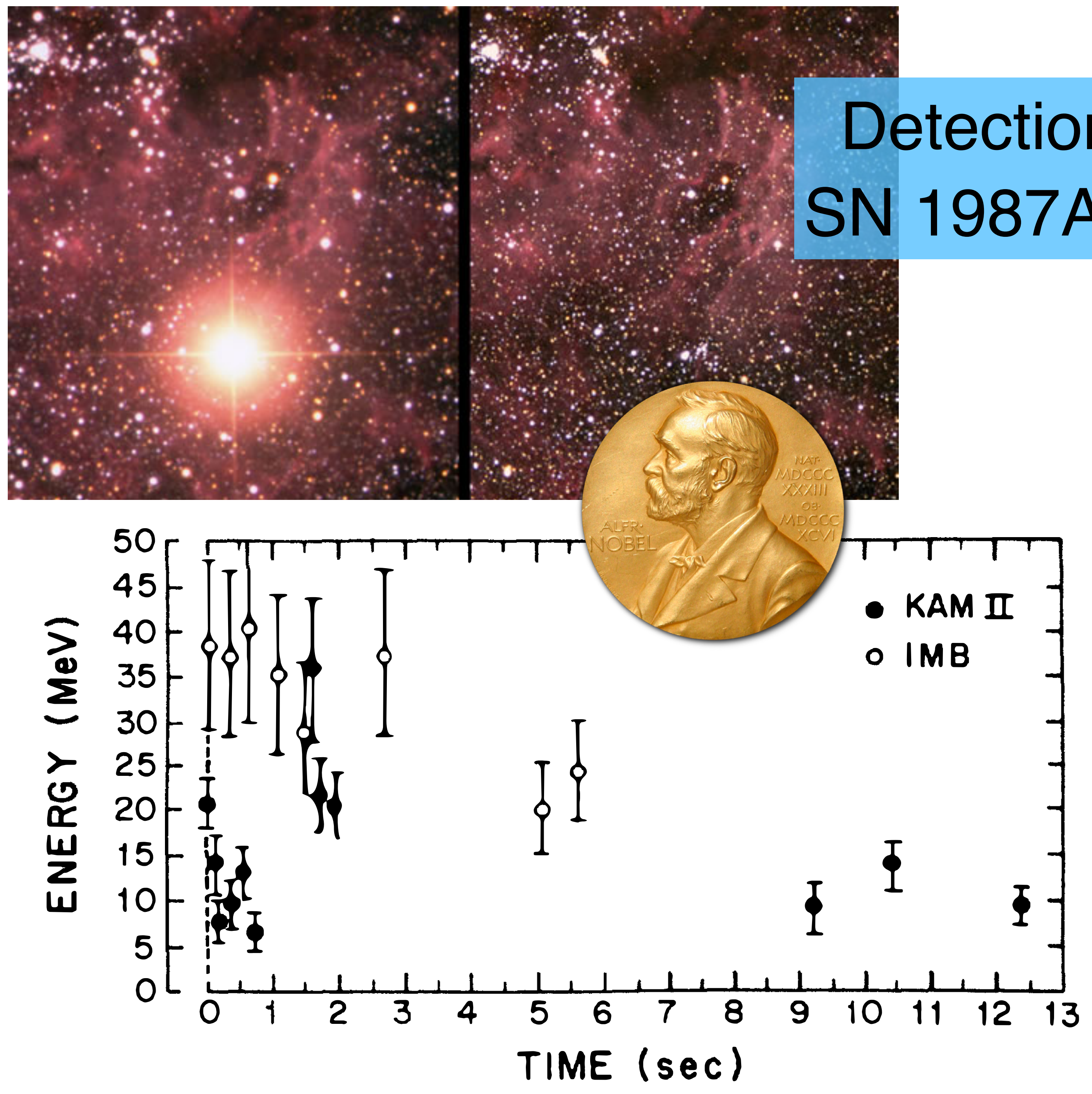
次世代検出器における広いエネルギー範囲での超新星背景ニュートリノフラックス解析に向けた研究を始めてます。

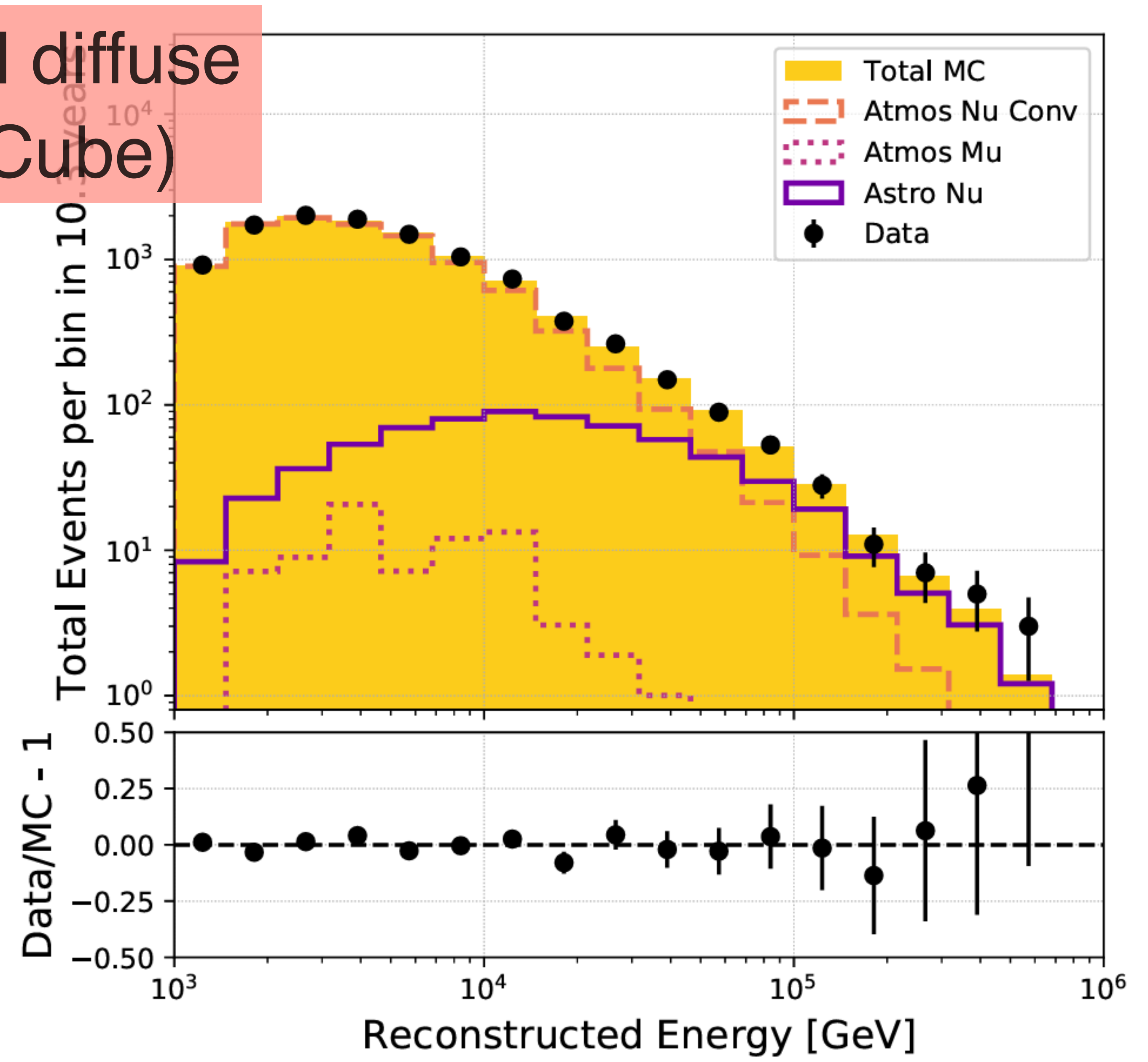
ASHIDA, Yosuke / 芦田 洋輔

Tohoku University / 東北大学

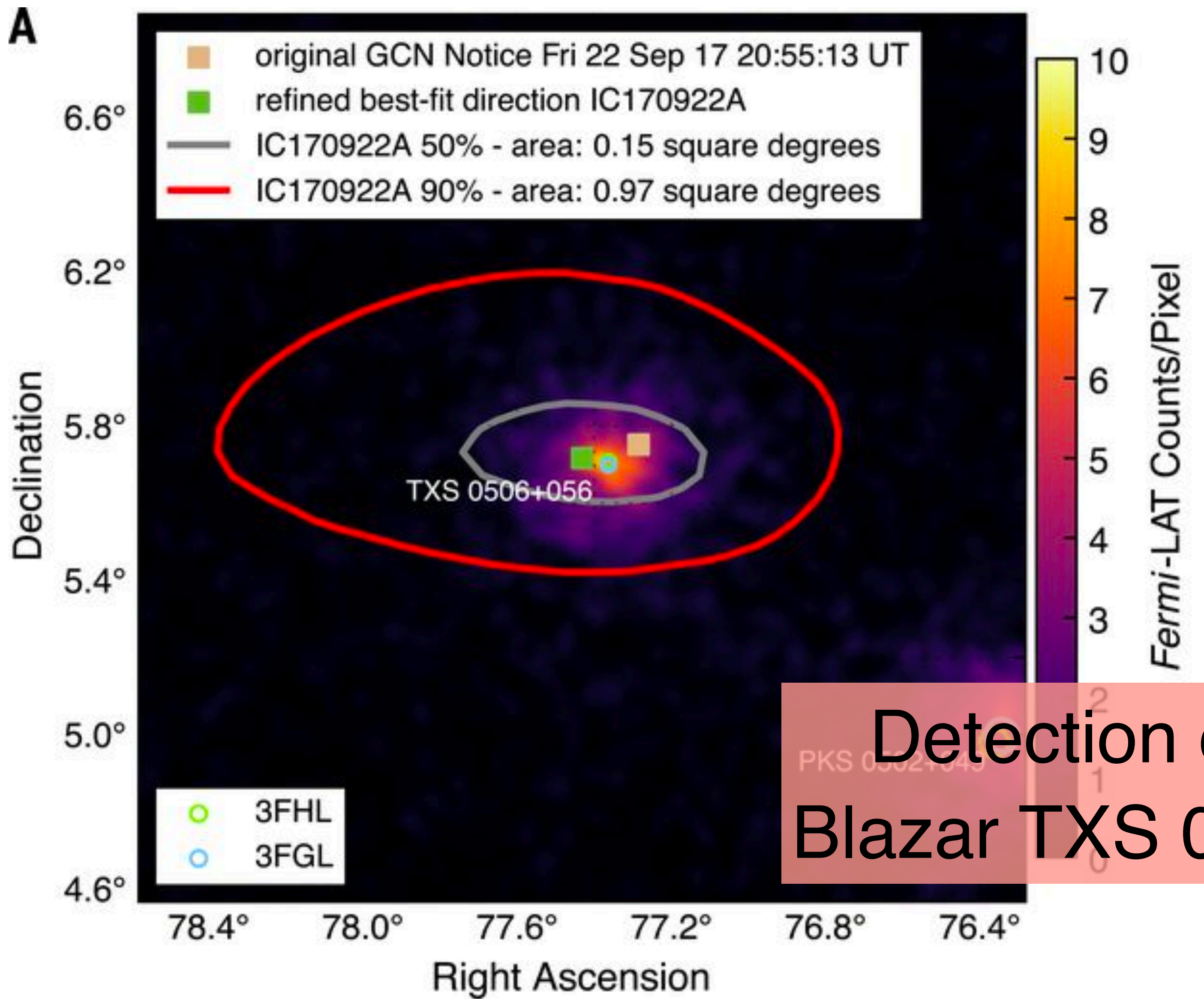
Detection of neutrinos from SN 1987A (Kamiokande else)



Confirmation of astrophysical diffuse high-energy neutrinos (IceCube)



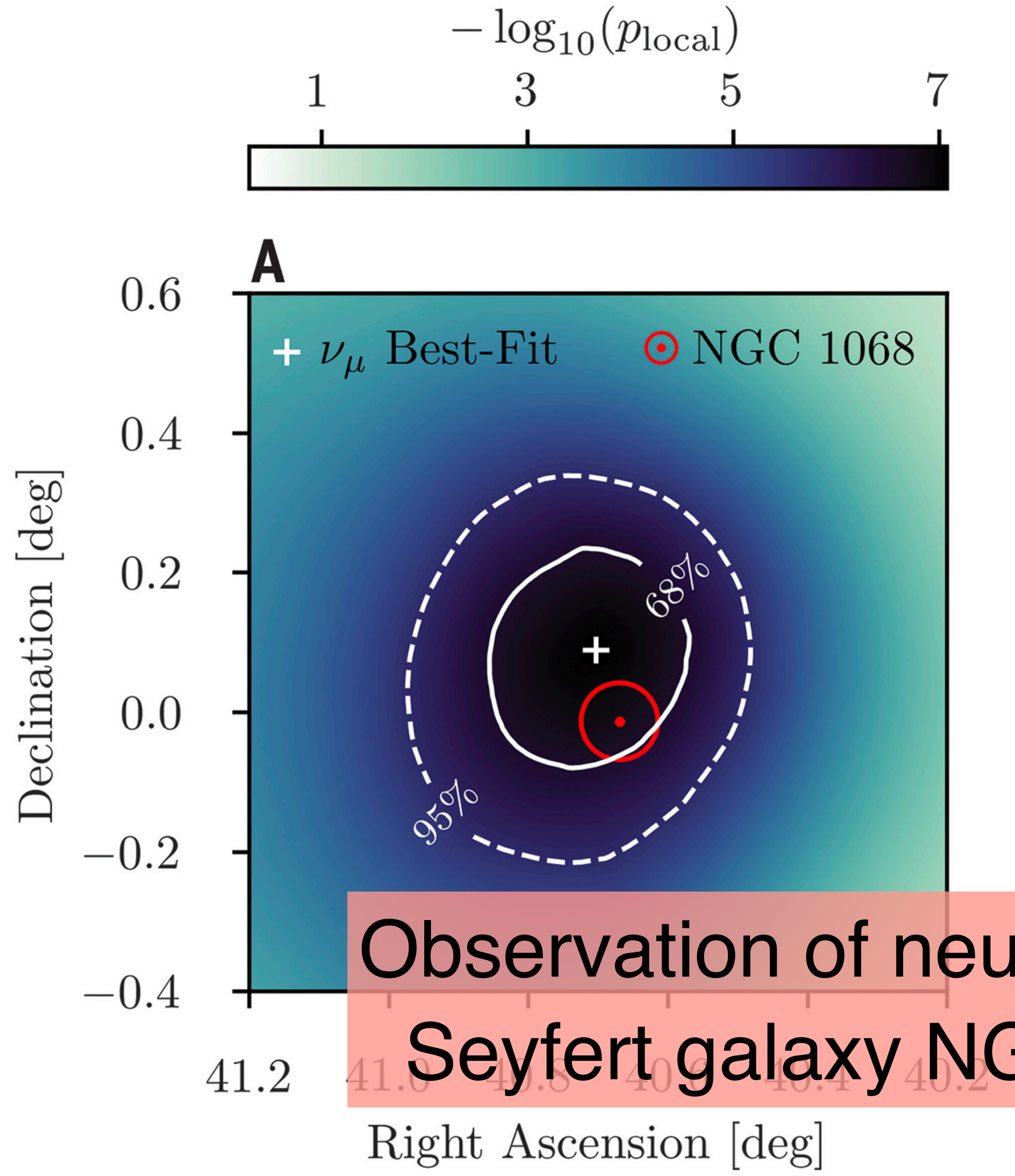
Detection of a neutrino from Blazar TXS 0506+056 (IceCube)



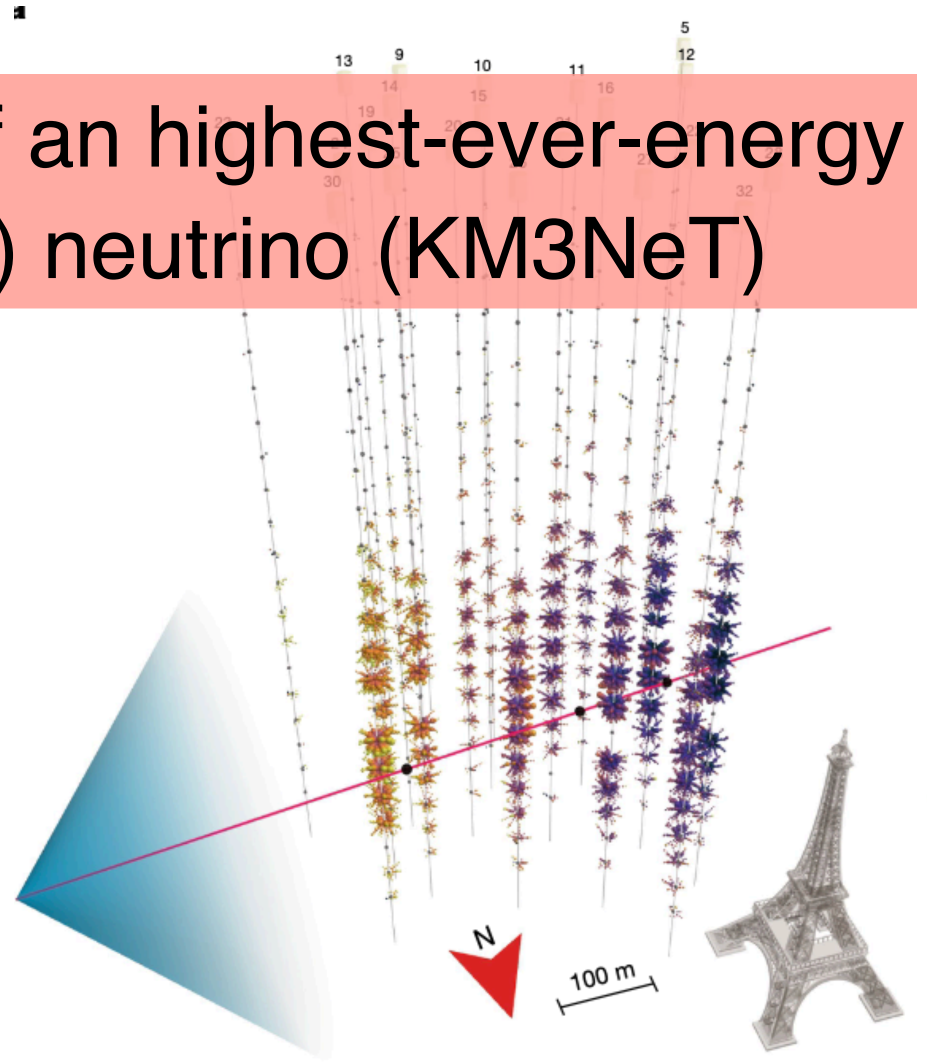
thermal

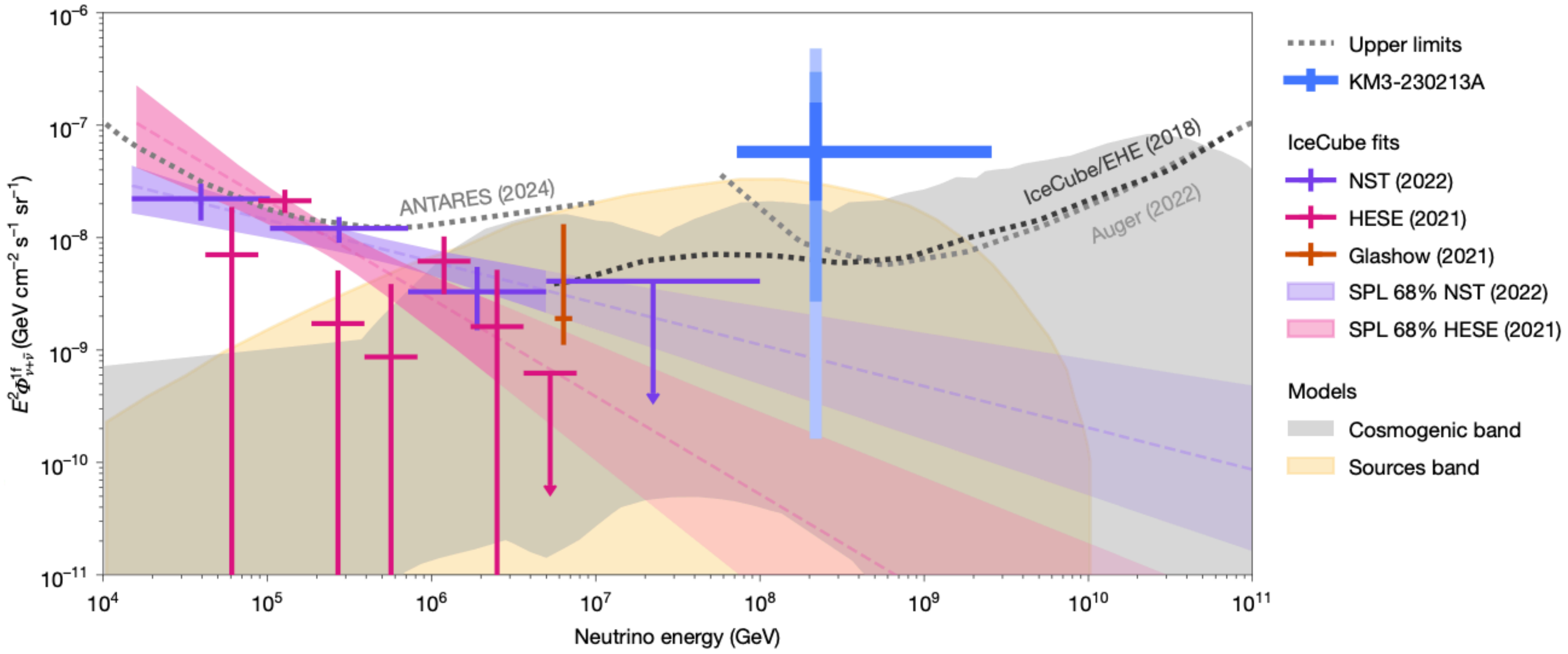
non-thermal

Observation of neutrino emission from Seyfert galaxy NGC 1068 (IceCube)

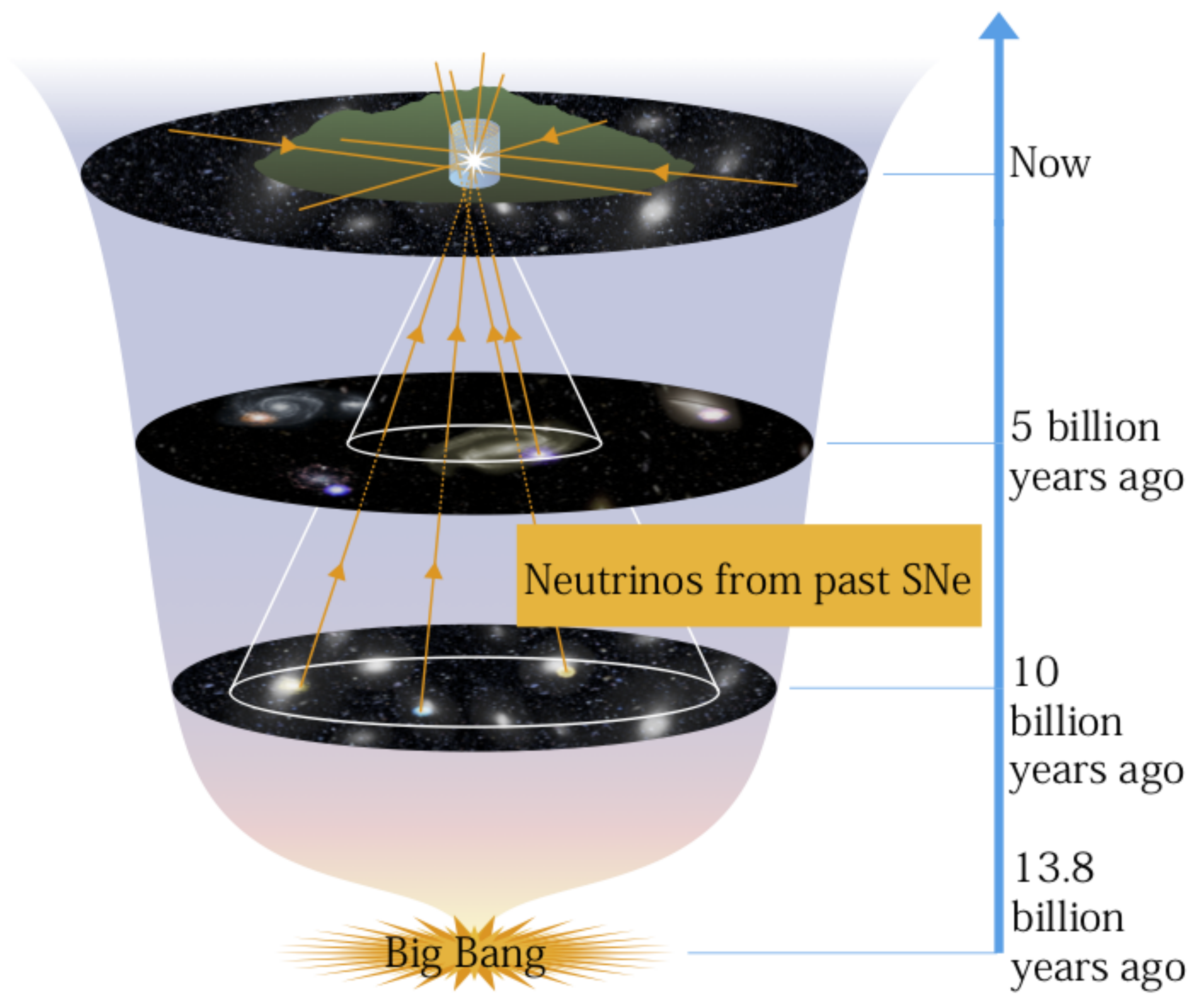


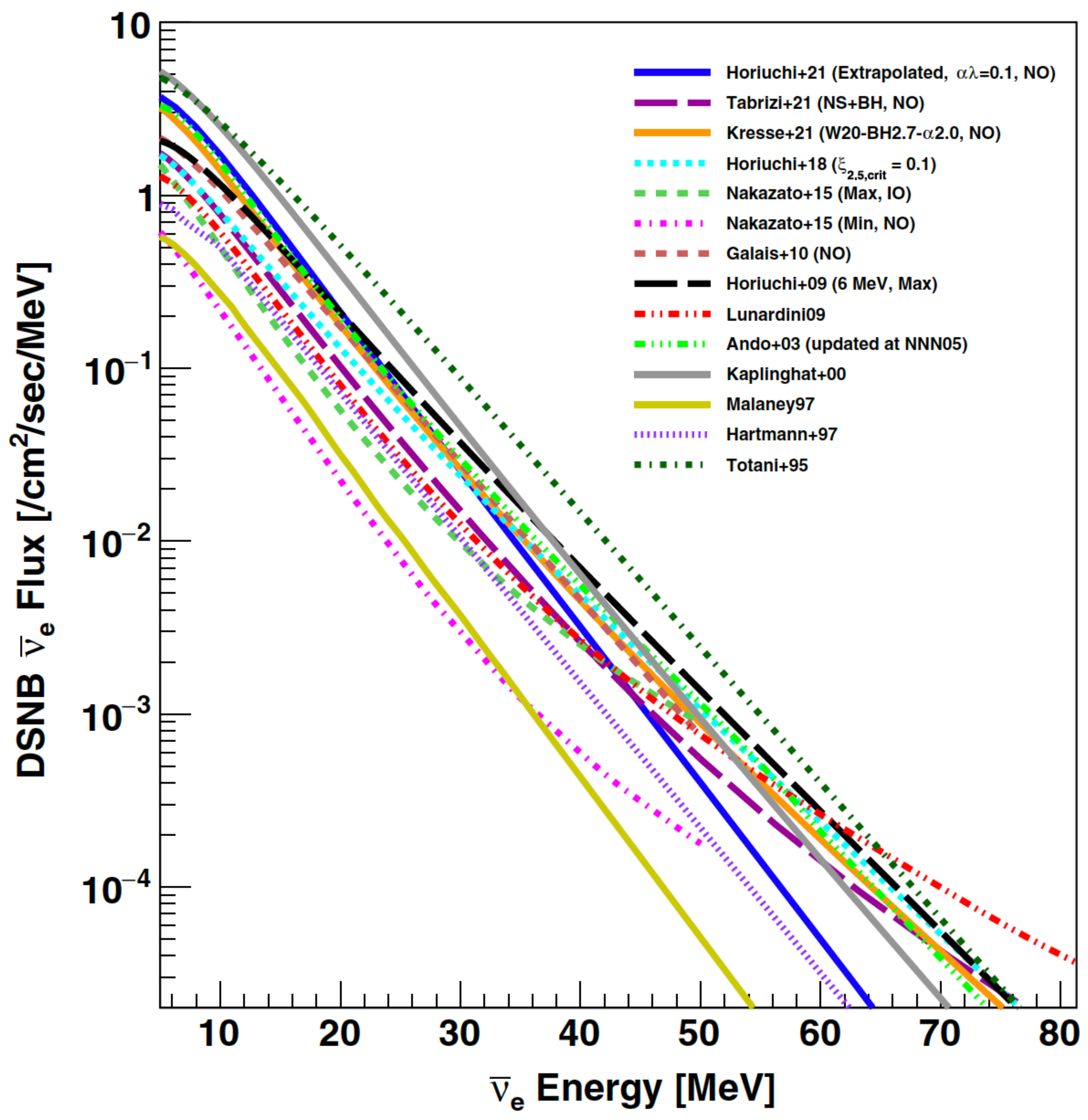
Observation of an highest-ever-energy (~220 PeV) neutrino (KM3NeT)





DSNB would be a new, unique probe in a neutrino astronomy program in the next decade!!





Achievements in 新学術 & 学術変革

The Astrophysical Journal, 937:30 (11pp), 2022 September 20

2022

https://doi.org/10.3847/1538-4357/ac8a46

OPEN ACCESS

CrossMark

Exploring the Fate of Stellar Core Collapse with Supernova Relic Neutrinos

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Received 2022 April 15; revised 2022 August 11; accepted 2022 August 15; published 2022 September 21

In collaboration with K. Nakazato (Kyushu), T. Tsujimoto (NAOJ), and R. Akaho (Waseda)

The Astrophysical Journal, 953:151 (9pp), 2023 August 20

2023

https://doi.org/10.3847/1538-4357/ace3ba

OPEN ACCESS

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Diffuse Neutrino Flux Based on the Rates of Core-collapse Supernovae and Black Hole Formation Deduced from a Novel Galactic Chemical Evolution Model

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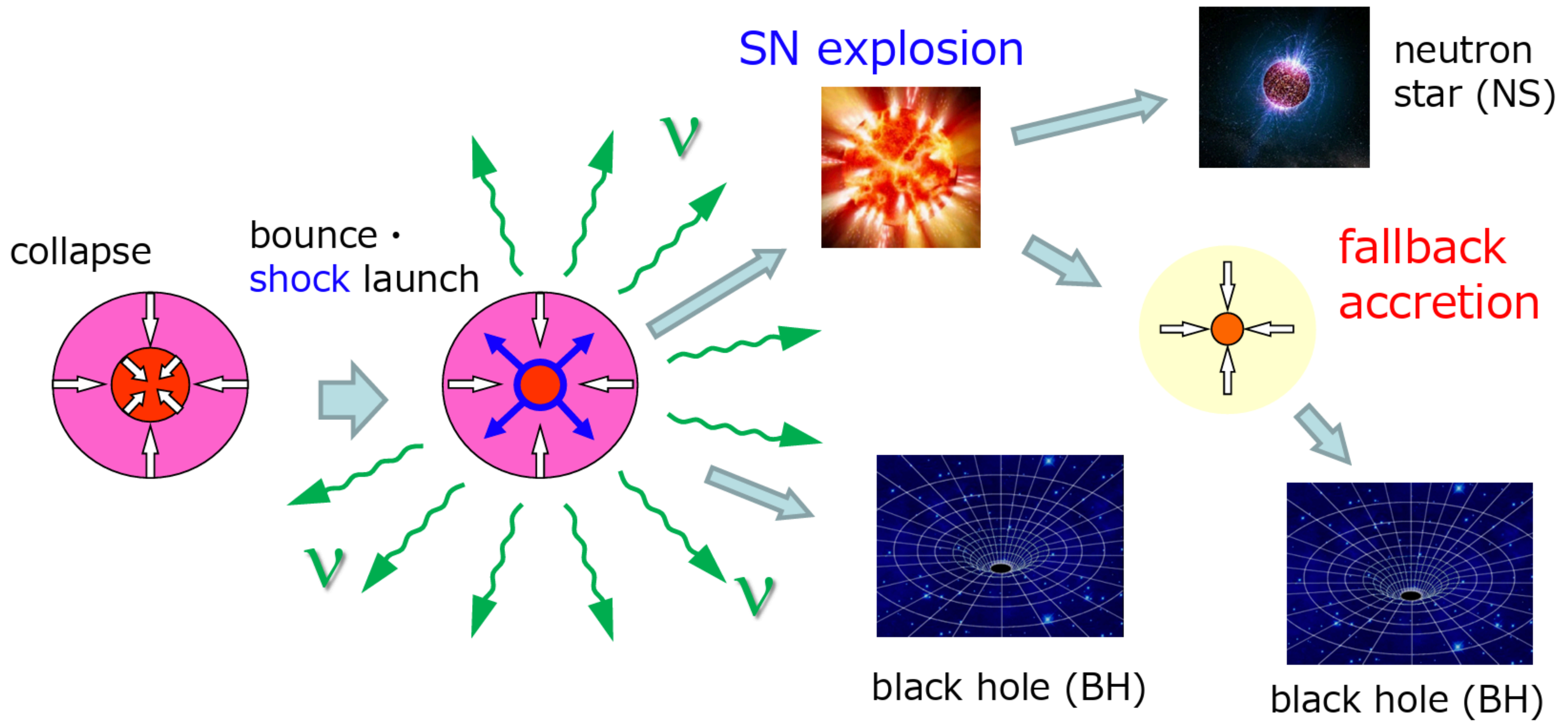
[2] Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI 53706, USA
[3] Faculty of Arts and Science, Kyushu University, Fukuoka 819-0395, Japan
[4] National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
Received 2023 May 22; revised 2023 July 1; accepted 2023 July 2; published 2023 August 14

Particularly focused on **BH-forming CCSNe** and **chemical evolution of galaxy**



from K. Nakazato

The Astrophysical Journal, 975:71 (10pp), 2024 November 1

2024

https://doi.org/10.3847/1538-4357/ad7826

OPEN ACCESS

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Impacts of Black-hole-forming Supernova Explosions on the Diffuse Neutrino Background

Ken'ichiro Nakazato[1], Ryuichiro Akaho[2], Yosuke Ashida[3], and Takuji Tsujimoto[4]
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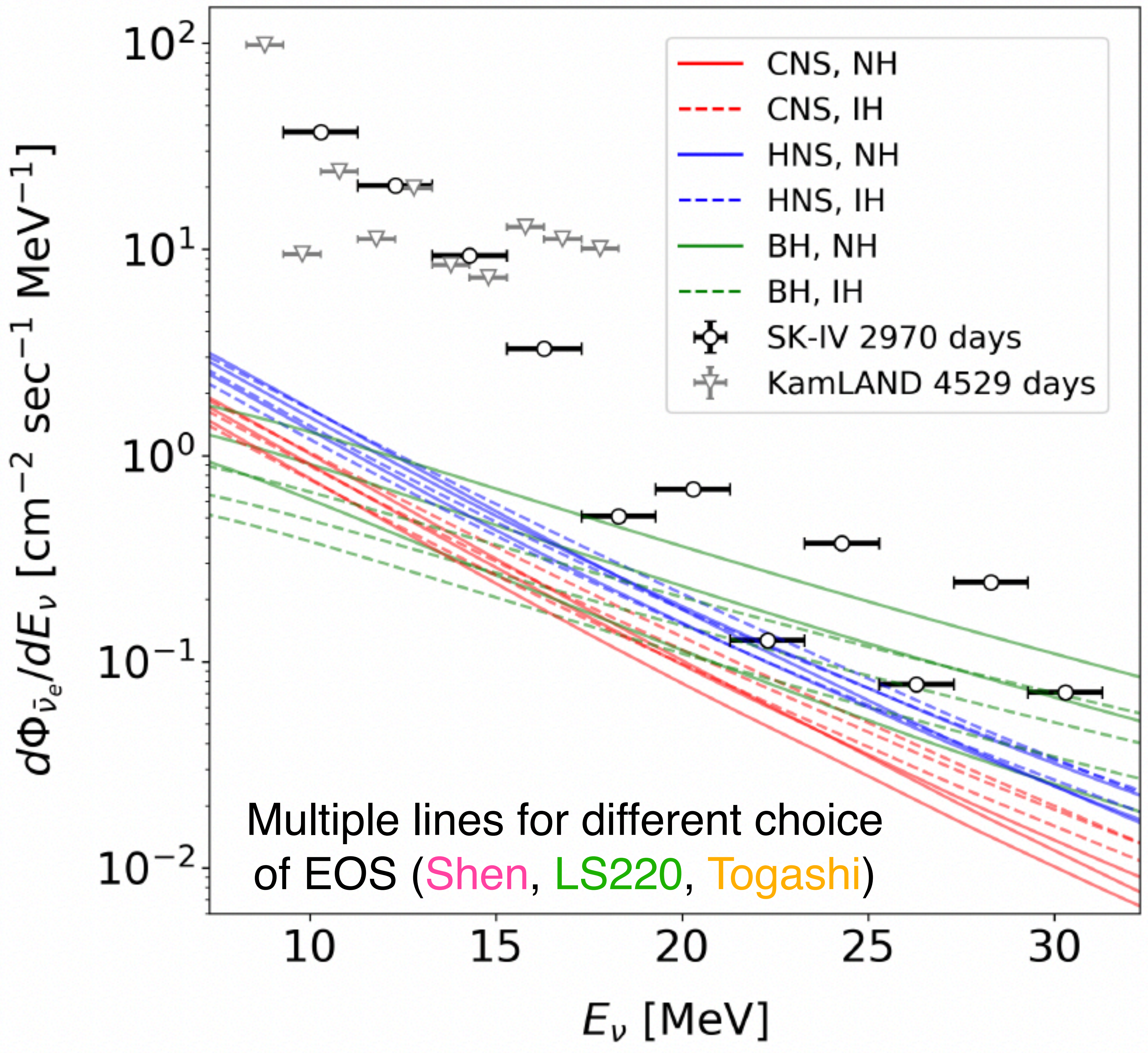
Received 2024 June 19; revised 2024 September 4; accepted 2024 September 5; published 2024 October 25

[1] Dependence on Fate of Core Collapse

- Emitted ν spectrum is expected to depend on the remnant after core collapse ("*fate*").
  - Information about the fate are accessible by other observations (pulser, failed SN monitoring, GW etc).

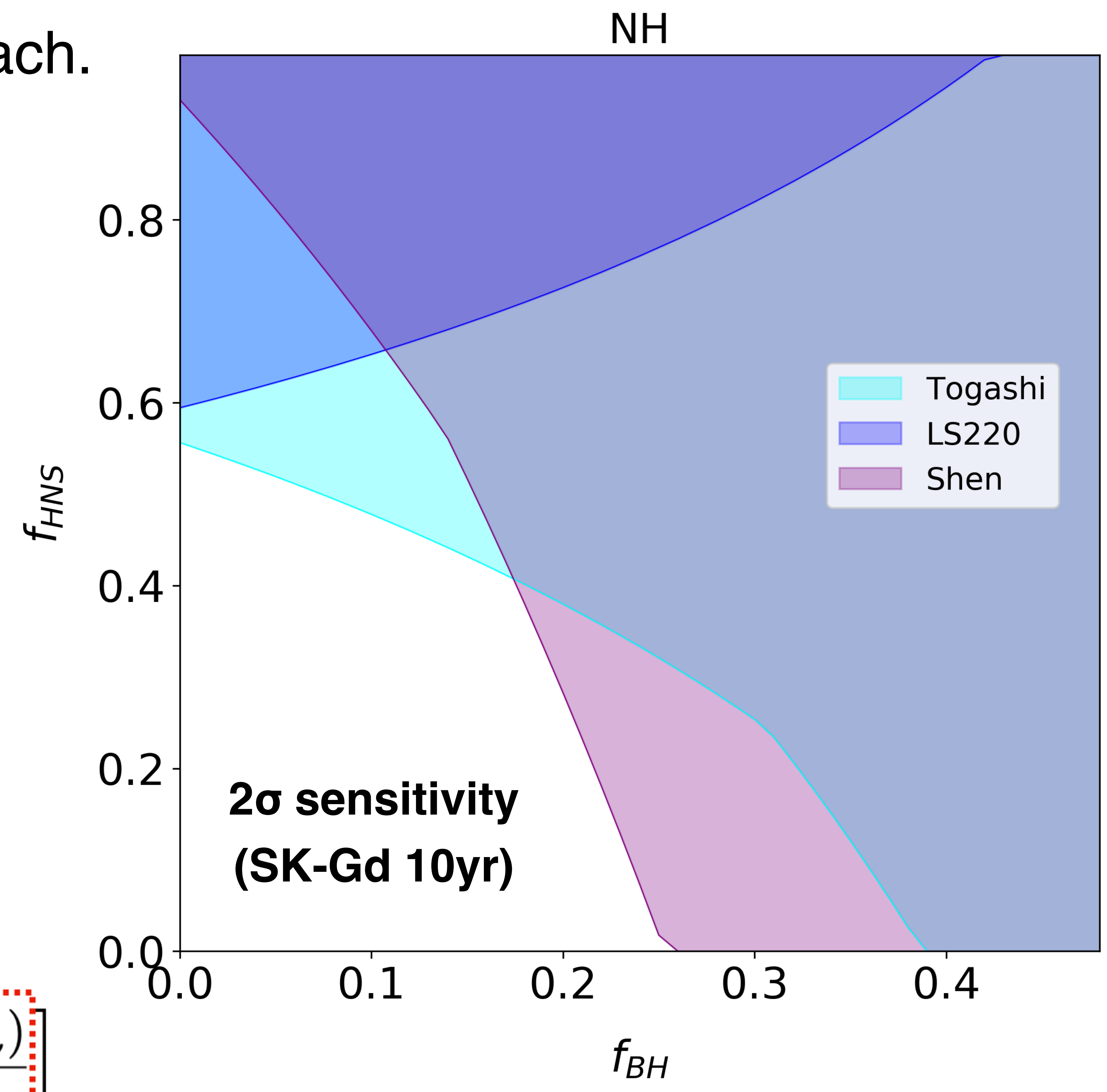
- Consider three major cases as a fate and calculate DSNB flux for each.
  - Canonical mass neutron stars (~1.4$M_{\rm sun}$)
  - High mass neutron stars (~1.7$M_{\rm sun}$)
  - Black holes (failed SNe)



[1] Experimental Constraint

- Emitted ν spectrum is expected to depend on the remnant after core collapse ("*fate*").
  - Information about the fate are accessible by other observations (pulsar, failed SN monitoring, GW etc).

- Consider three major cases as a fate and calculate DSNB flux for each.
  - Canonical mass neutron stars (~1.4$M_{\rm sun}$)
  - High mass neutron stars (~1.7$M_{\rm sun}$)
  - Black holes (failed SNe)
  - The calculated DSNB fluxes from these three are mixed with fractional parameters, $\boldsymbol{f}_{\rm HNS}$ and $\boldsymbol{f}_{\rm BH}$, which are to be measured.



DSNB flux at Earth

Neutrino spectrum from a core-collapse

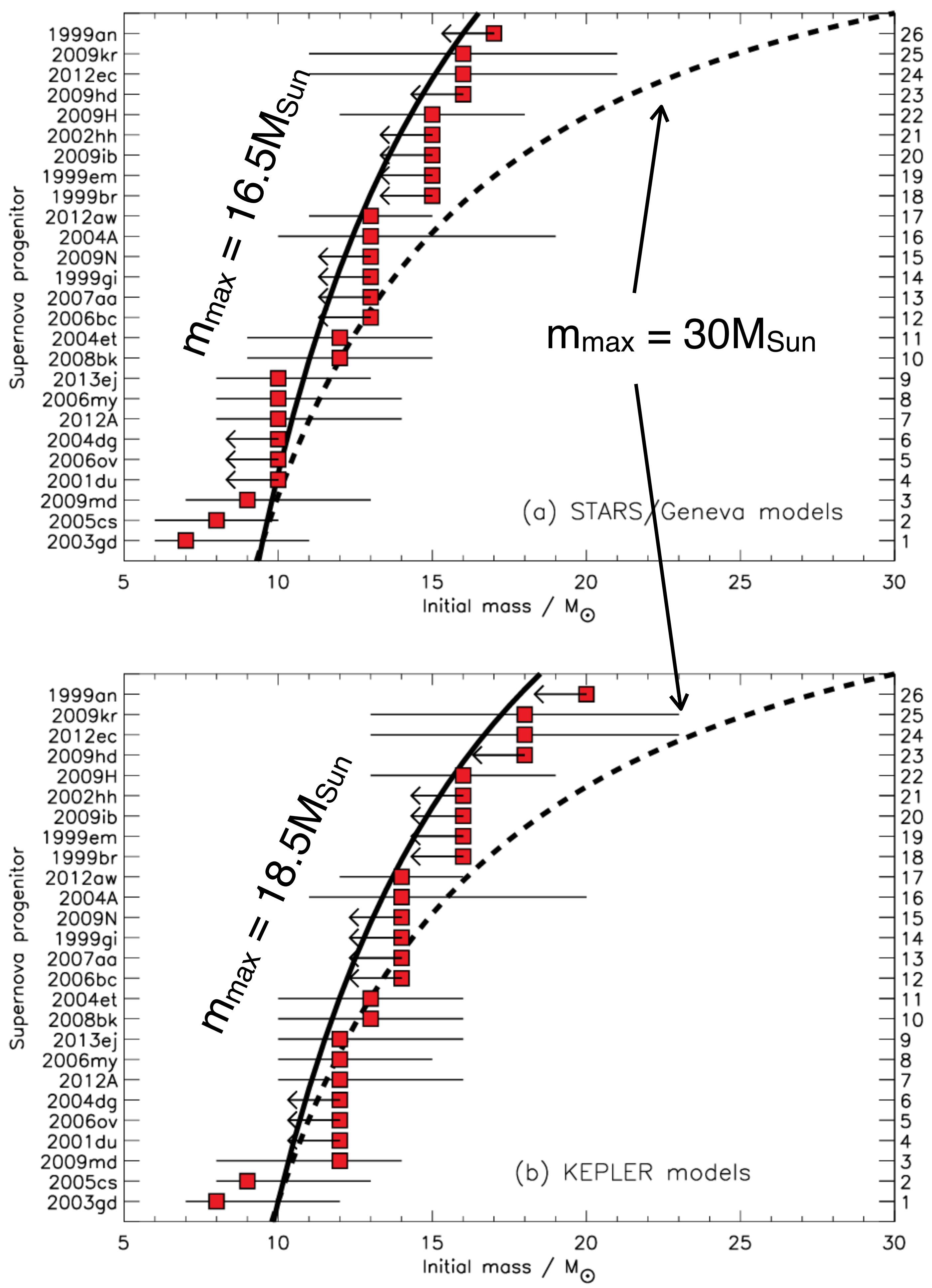
$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^{z_{\rm max}} R_{\rm CC}(z)\boxed{\left\langle\frac{dN(E'_\nu)}{dE'_\nu}\right\rangle} \times \frac{dz}{H_0\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}}$$

$$\left\langle\frac{dN(E'_\nu)}{dE'_\nu}\right\rangle = f_{\rm BH}\boxed{\frac{dN_{\rm BH}(E'_\nu)}{dE'_\nu}} + (1-f_{\rm BH}) \times \left[f_{\rm HNS}\boxed{\frac{dN_{\rm HNS}(E'_\nu)}{dE'_\nu}} + (1-f_{\rm HNS})\boxed{\frac{dN_{\rm CNS}(E'_\nu)}{dE'_\nu}}\right]$$

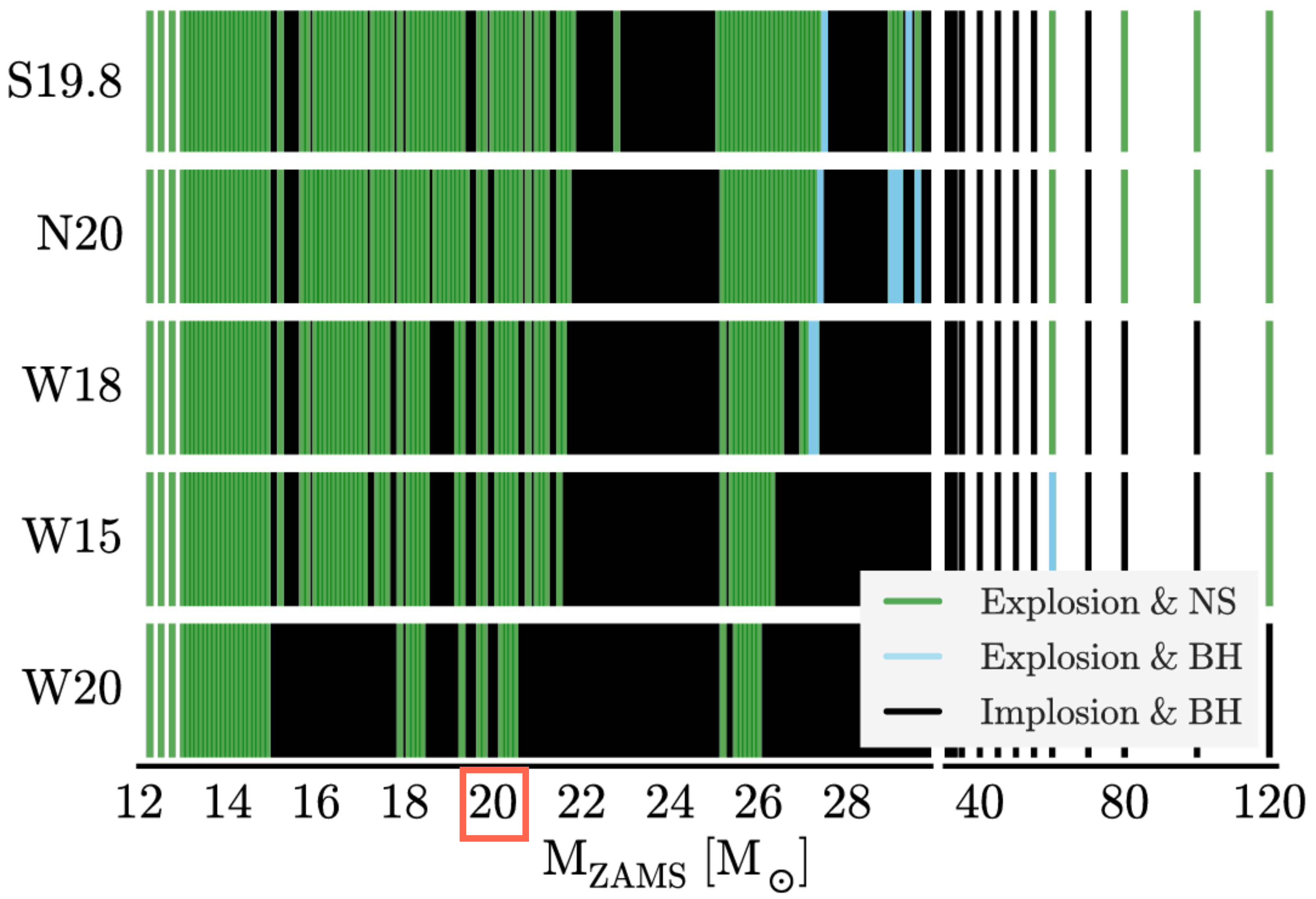
[2] CCSN Mass Limit

- We set the maximum mass of progenitors for successful explosions to **18*M*sun**.
  - Observationally, m_{min} ~ 8M_{sun} and m_{max} ~ 18M_{sun} are supported.
  - There is a theoretical work that implies failed SNe above ~20M_{sun}.
- Many galactic chemical evolution schemes adopt a high m_{max} (50~100M_{sun}).
  - Our m_{max} =18M_{sun} assumption reduces the number of CCSNe to **~70%**.
  - Accordingly, the total amount of heavy elements is reduced to **~50%**.

S. J. Smartt, PASA 32 (2015)



T. Sukhbold et al., ApJ 821, 38 (2016)



[2] Variable IMF

T. Tsujimoto, MNRAS 518, 3475 (2023)

- In order to achieve consistency with observed chemical abundance, we propose a new evolution model.
- We categorize galaxies into five and assume different initial mass functions (IMF) depending types.
- The fraction for BH formation from this model is **33~42%** (higher rate than many other DSNB models).

How star formation proceeds?

moderate mode

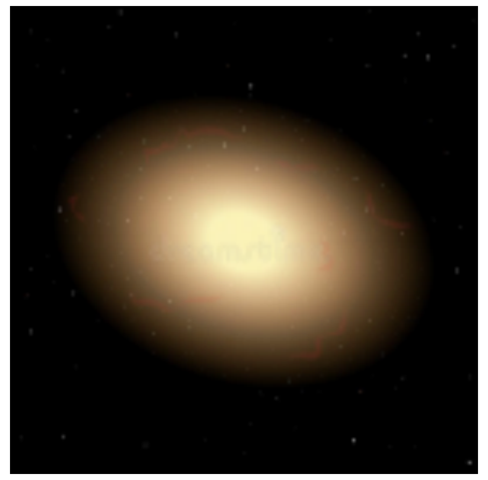
late-type galaxies (Sbc, Scd, Sdm)

Salpeter IMF

(x = –1.35)

bursting mode

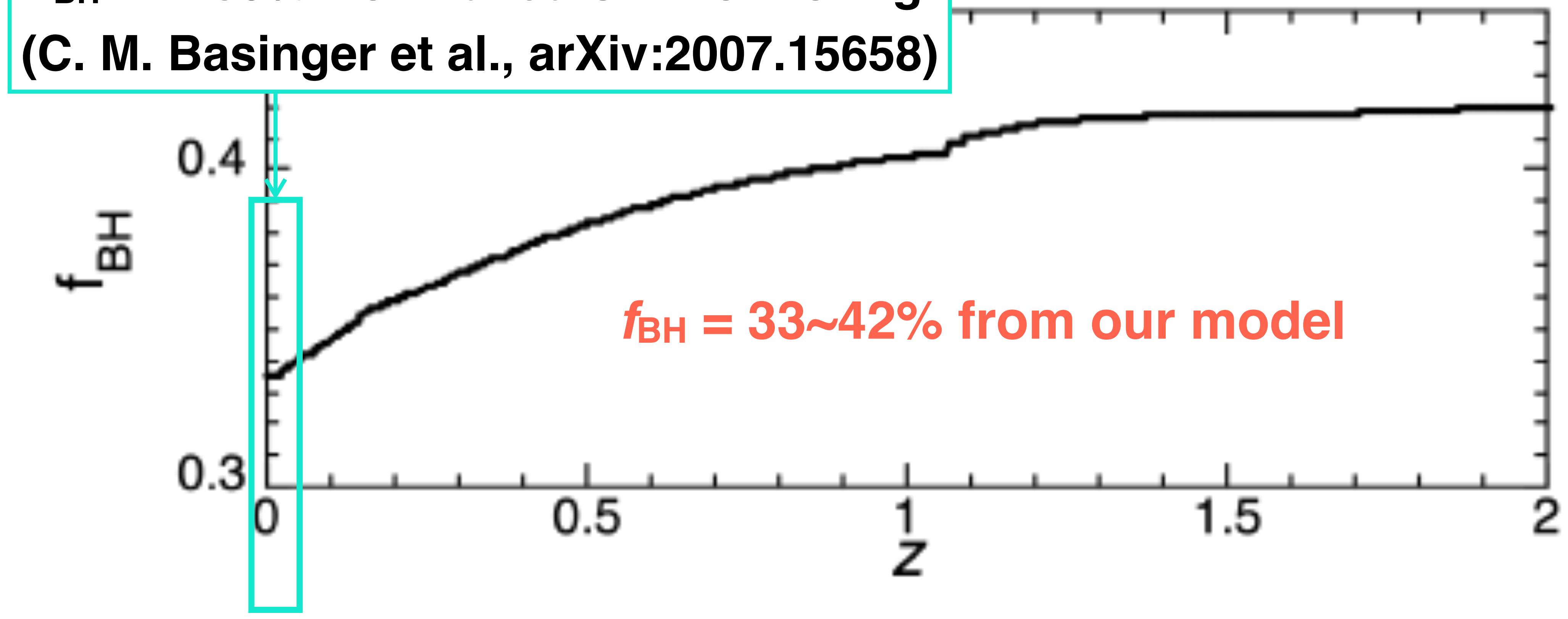
early-type galaxies (E/S0, Sab)



Flat IMF

(x = –0.9)

f_{BH} = 4~39% from failed SN monitoring (C. M. Basinger et al., arXiv:2007.15658)

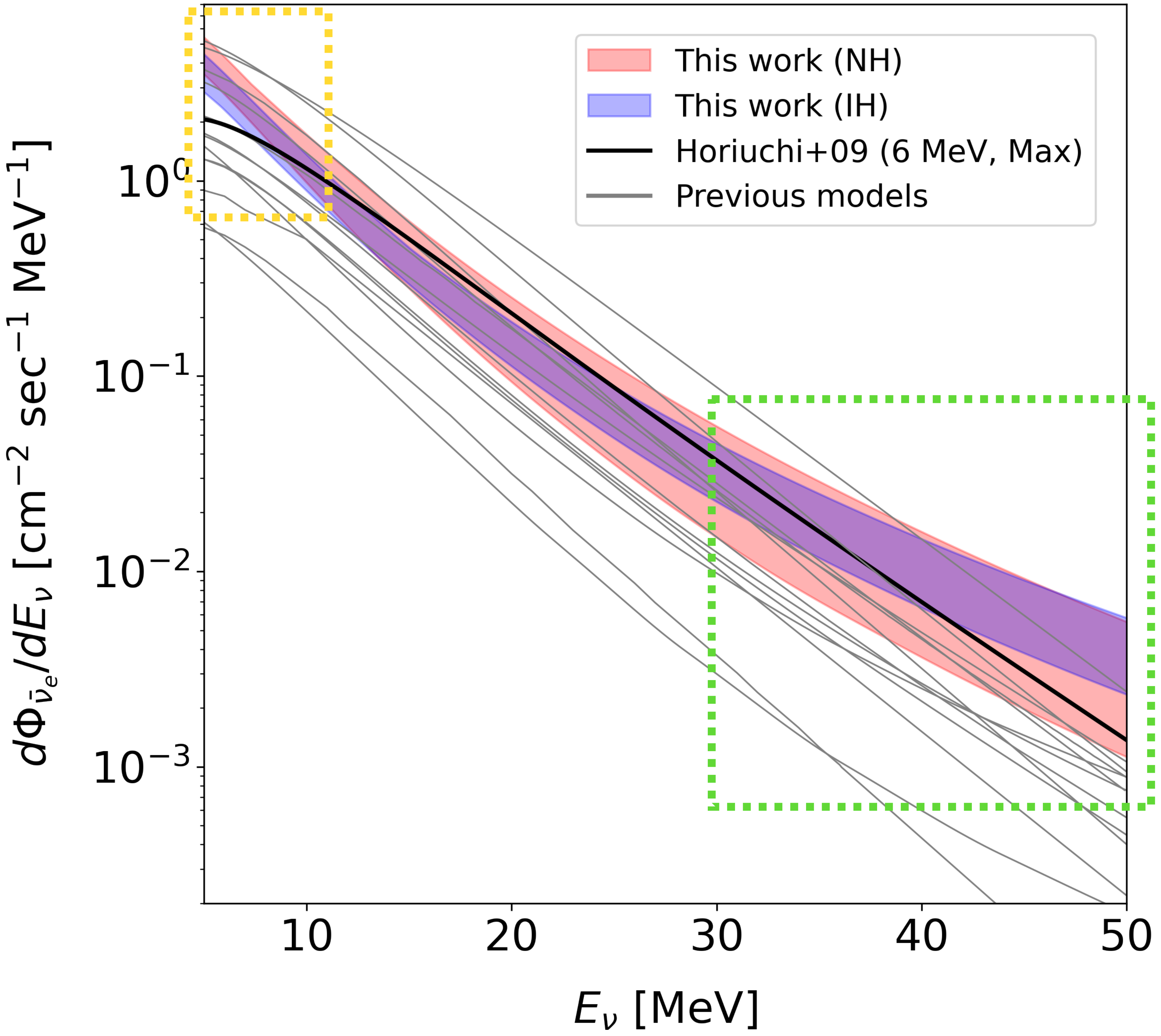


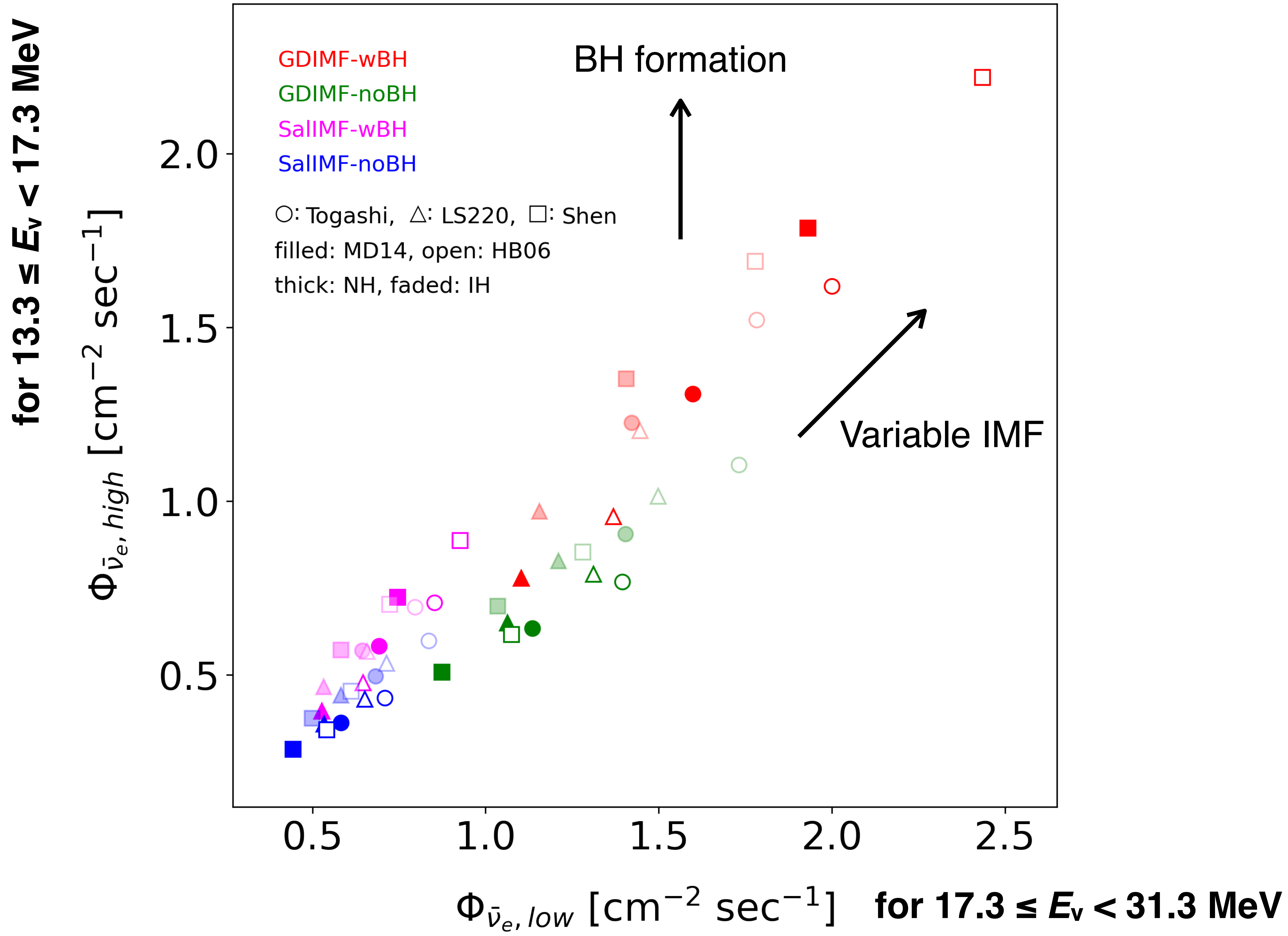
Our model nomenclature

Name	IMF form	BH treatment
GDIMF-wBH (ref.)	Variable	BHs for 18–100$M_\odot$
GDIMF-noBH	Variable	No BH
SalIMF-wBH	Salpeter	BHs for 18–100$M_\odot$
SalIMF-noBH	Salpeter	No BH

[2] Resulting DSNB Flux

- Our model shows DSNB flux enhancements at high and low energies.
- High energy (>30 MeV): Large contribution from BH formation.
- Low energy (<10 MeV): Redshifted neutrinos from early-type galaxies with large CCSN rates.



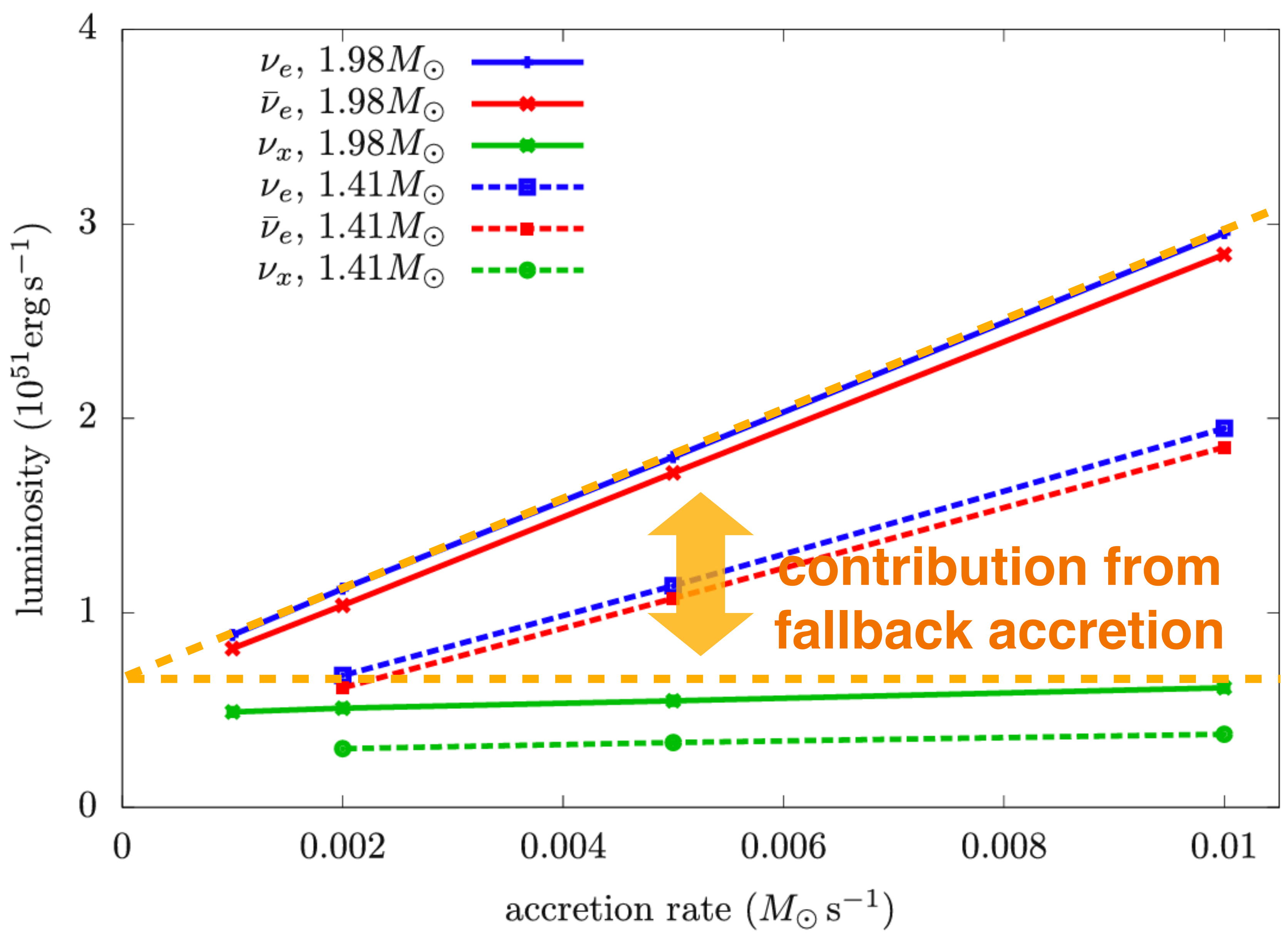


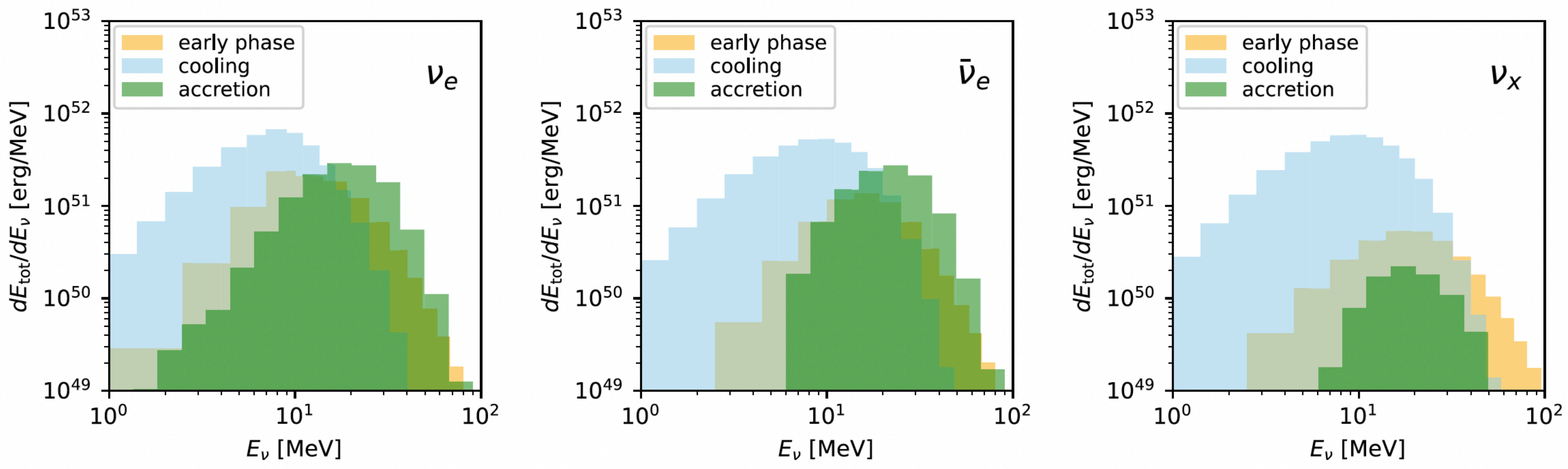
[3] Fallback-origin Neutrinos

R. Akaho et al., ApJ 960, 116 (2024)

- Utilizing a steady-state neutrino emission from fallback onto a PNS, three components are considered;
    1. Core collapse of a massive star
    2. Cooling of a $M_g = 1.98 M_{sun}$ PNS (corresponds to $M_b = 2.35 M_{sun}$)
    3. Fallback accretion of a total $0.35 M_{sun}$ (reaching maximum NS mass in Togashi EOS, $M_b = 2.70 M_{sun}$)

- Fallback-induced neutrinos have higher energies.

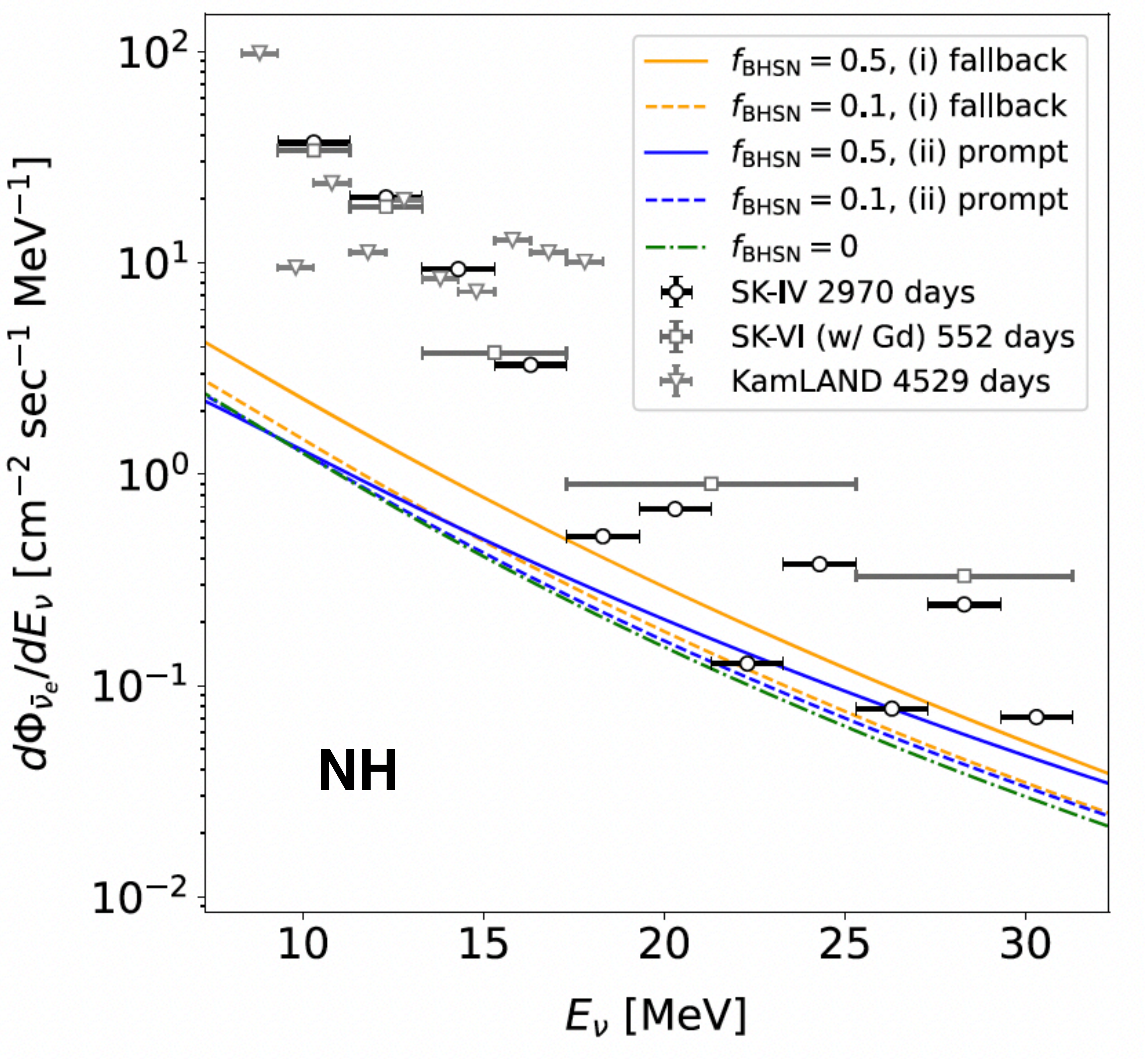


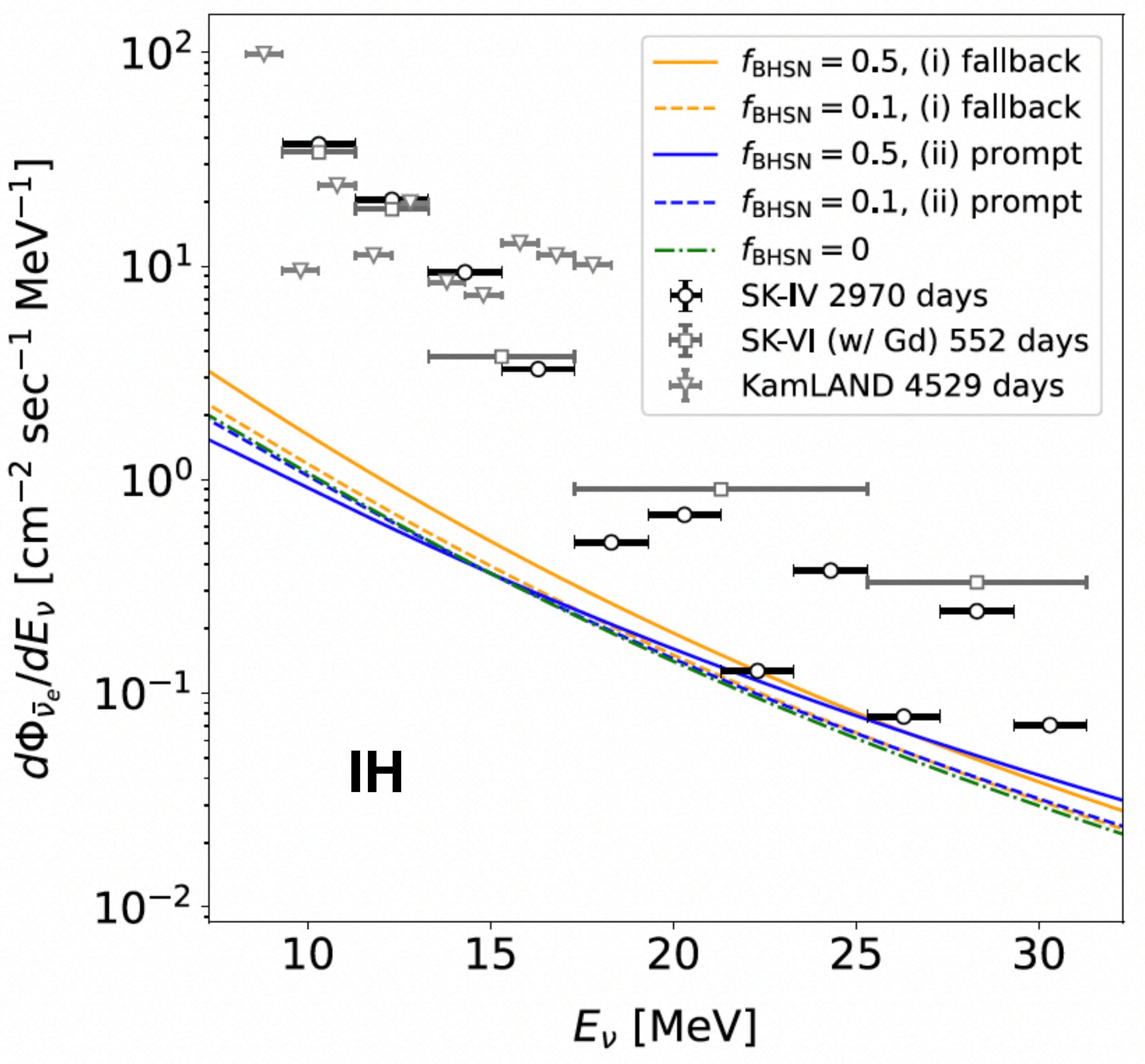


[3] Impact on DSNB Flux

- Fallback case shows larger flux than prompt BH formation case.
- NH case observes a larger impact due to electron-type neutrinos.
- $f_{\rm BHSN}$ = 0.5 case is already disfavored by the current limits.

fallback: 175 sec (0.002$M_{\rm sun}$ s^{-1})
prompt: O(1) sec (~failed)





Take Away from Theory Side

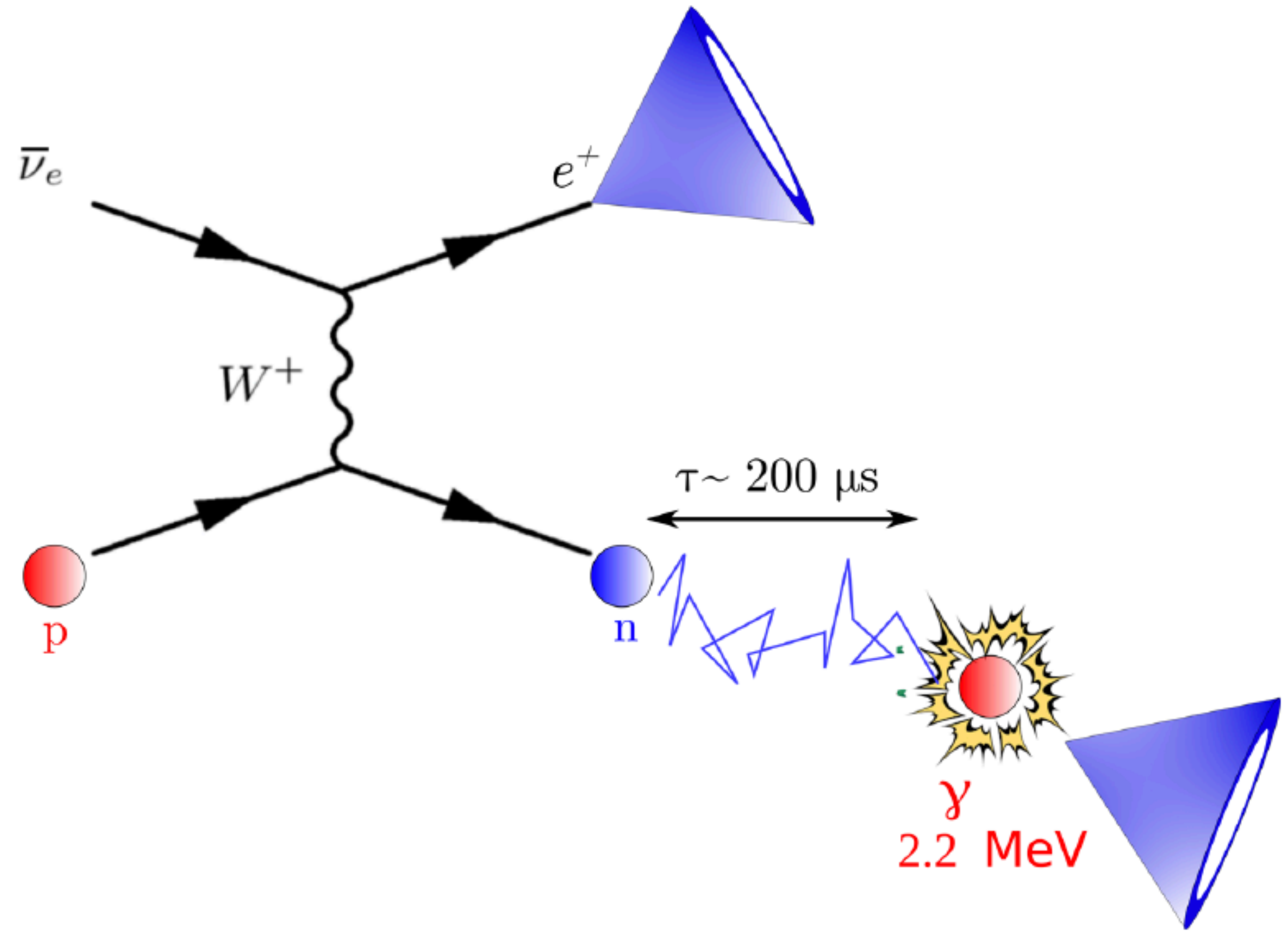
- Many models have been proposed for recent years, including ours.
- Some models show a characteristic flux shape, such as an enhancement at low or high energies.
- Those enhancements should reflect important astrophysical / astronomical assumptions.
    - Black hole formation
    - Variable IMF
    - etc

→ **Important to measure the DSNB flux over the wide energy range!**

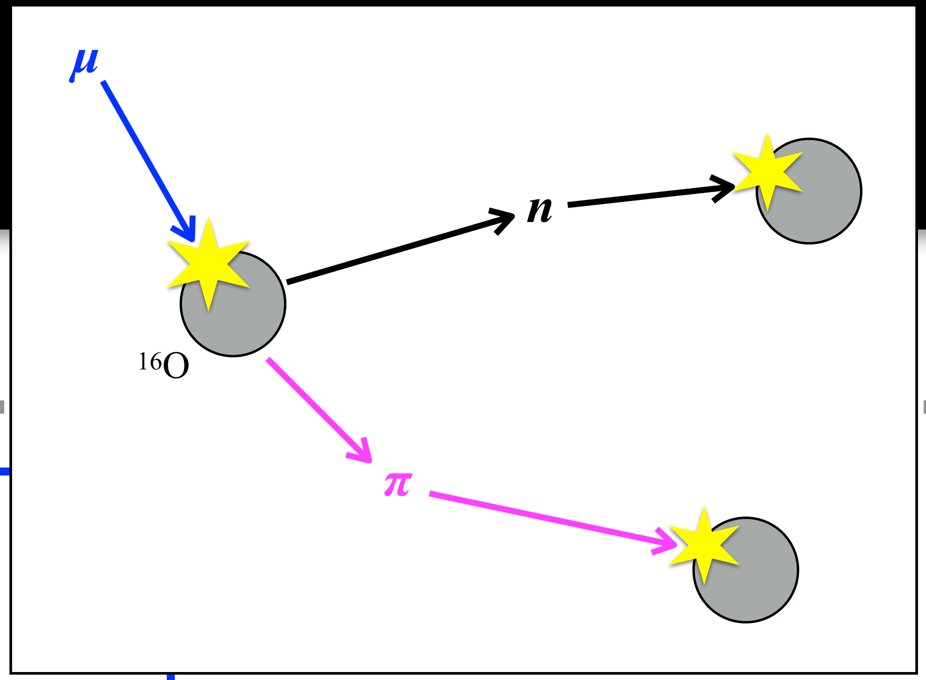
Experimental Search

- Signal = **inverse beta decay (IBD)**, $\bar{\nu}_e$ **+ p →** e^+ **+ n** (largest cross section)
  - e^+ = "*prompt*" signal (main signal range: **10~30 MeV**)
  - **n** = "*delayed*" signal via **γ-ray(s)** from thermal capture on hydrogen or gadolinium

- Many types of backgrounds mimicking this signature.
  - Atmospheric neutrinos
  - Radioactive isotopes produced by atmospheric muons
  - Solar neutrinos
  - Reactor neutrinos

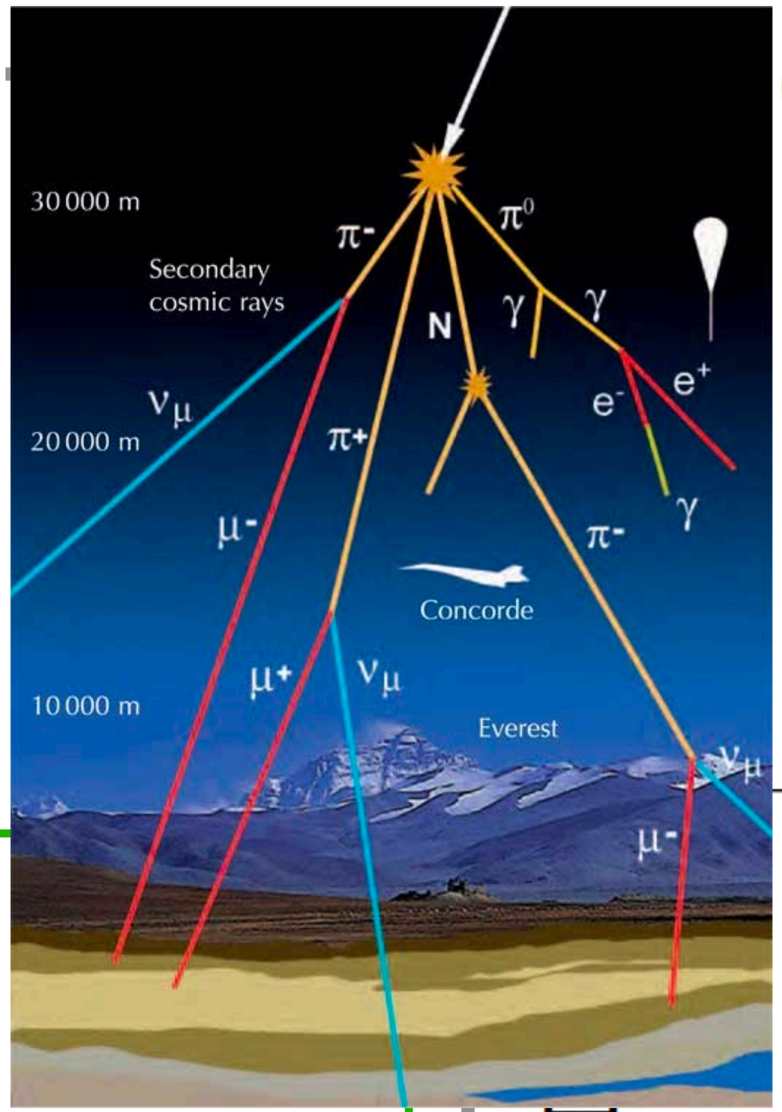


Background



Muon spallation

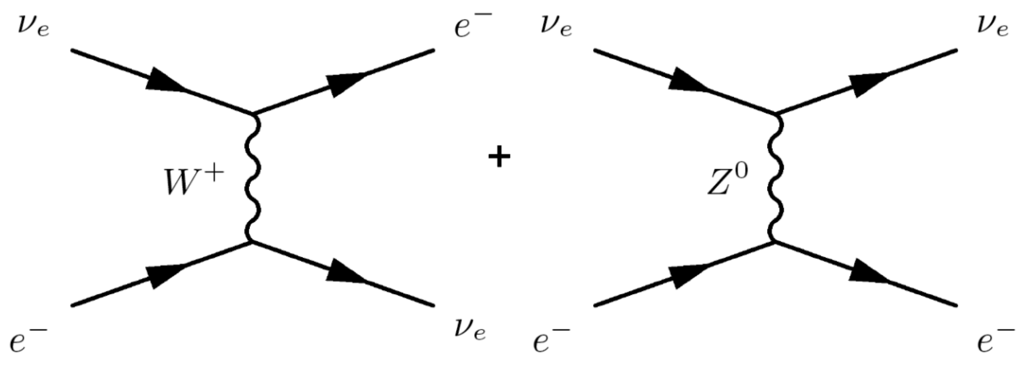
- Decay without neutron
- Decay with neutron (^{9}Li, etc)



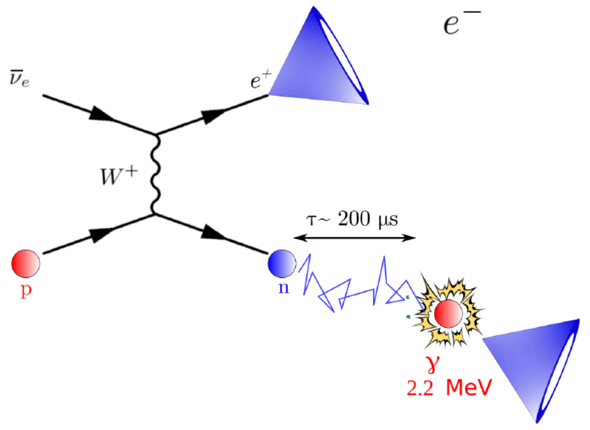
Atmospheric neutrinos

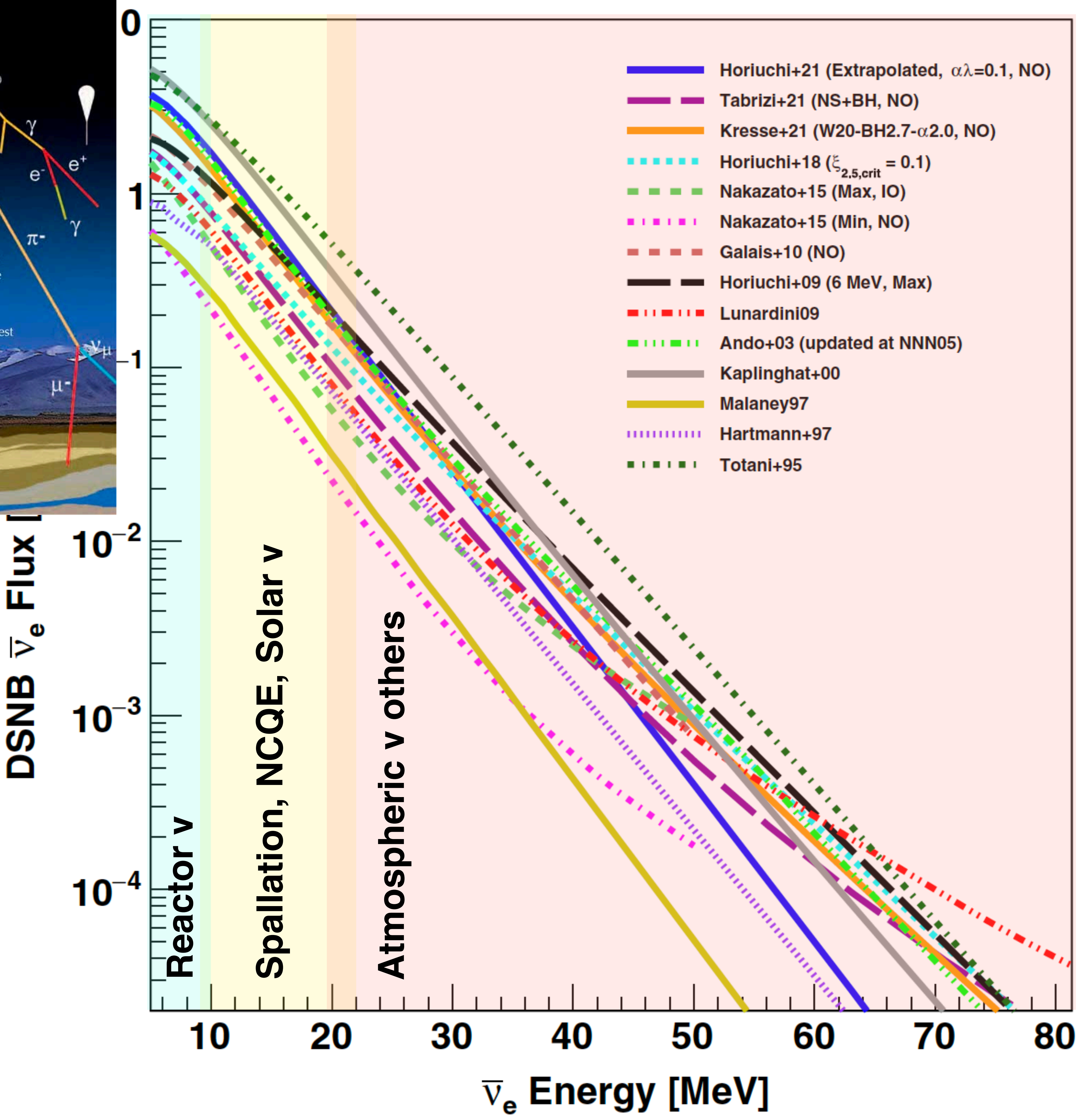
- Neutral-current quasielastic interactions (NCQE)
- $\nu_e/\overline{\nu}_e$ charged-current (CC) interactions
- Muon/pion-producing interactions (CCQE, CC1π, NC1π, etc)

Solar neutrinos (electron scattering)



Reactor neutrinos (IBD)





Telescopes in Upcoming Decade

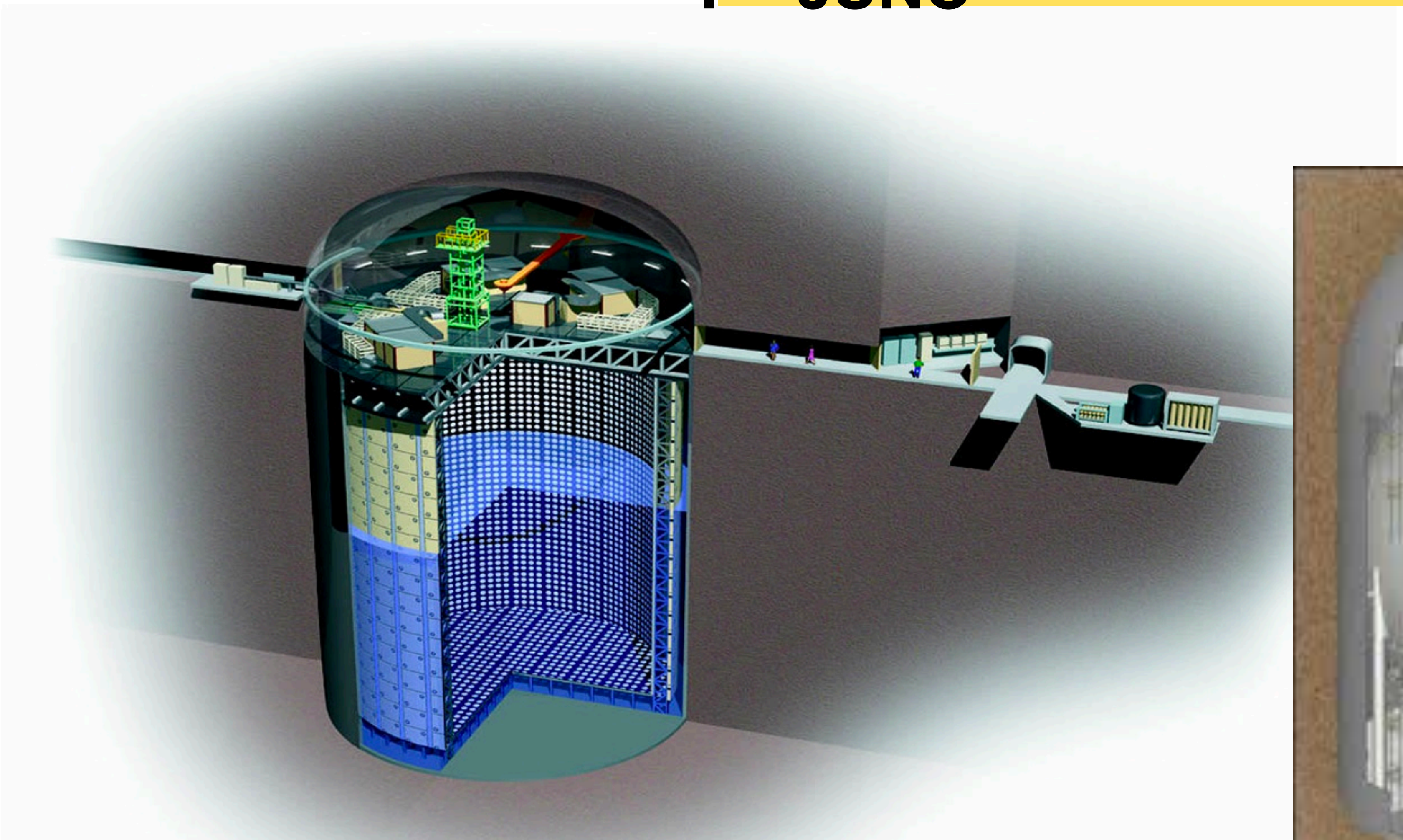
2025 2026 2027 2028

Super-K (since 1996; Gd since 2020) ?

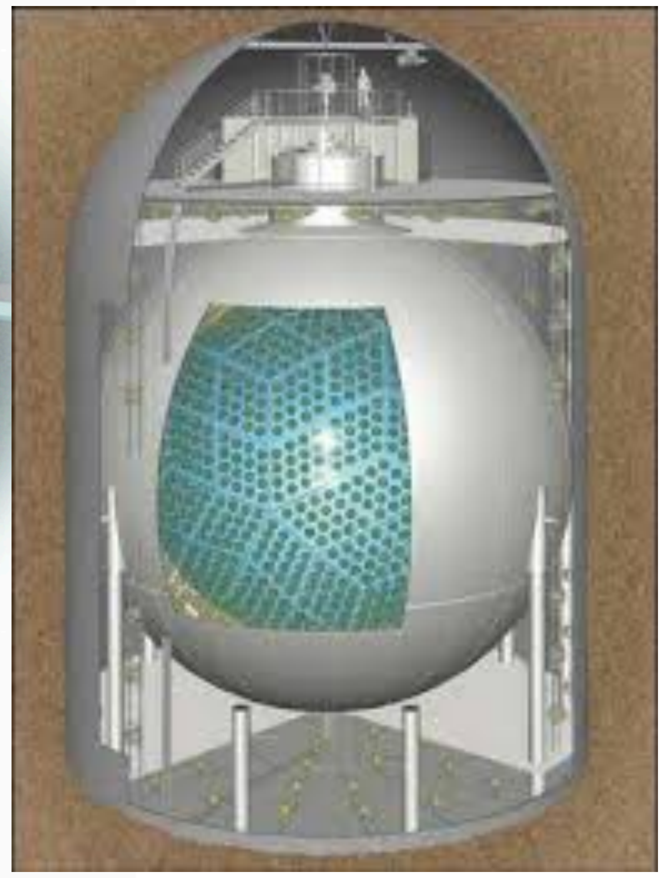
KamLAND (since 2002) ?

? JUNO

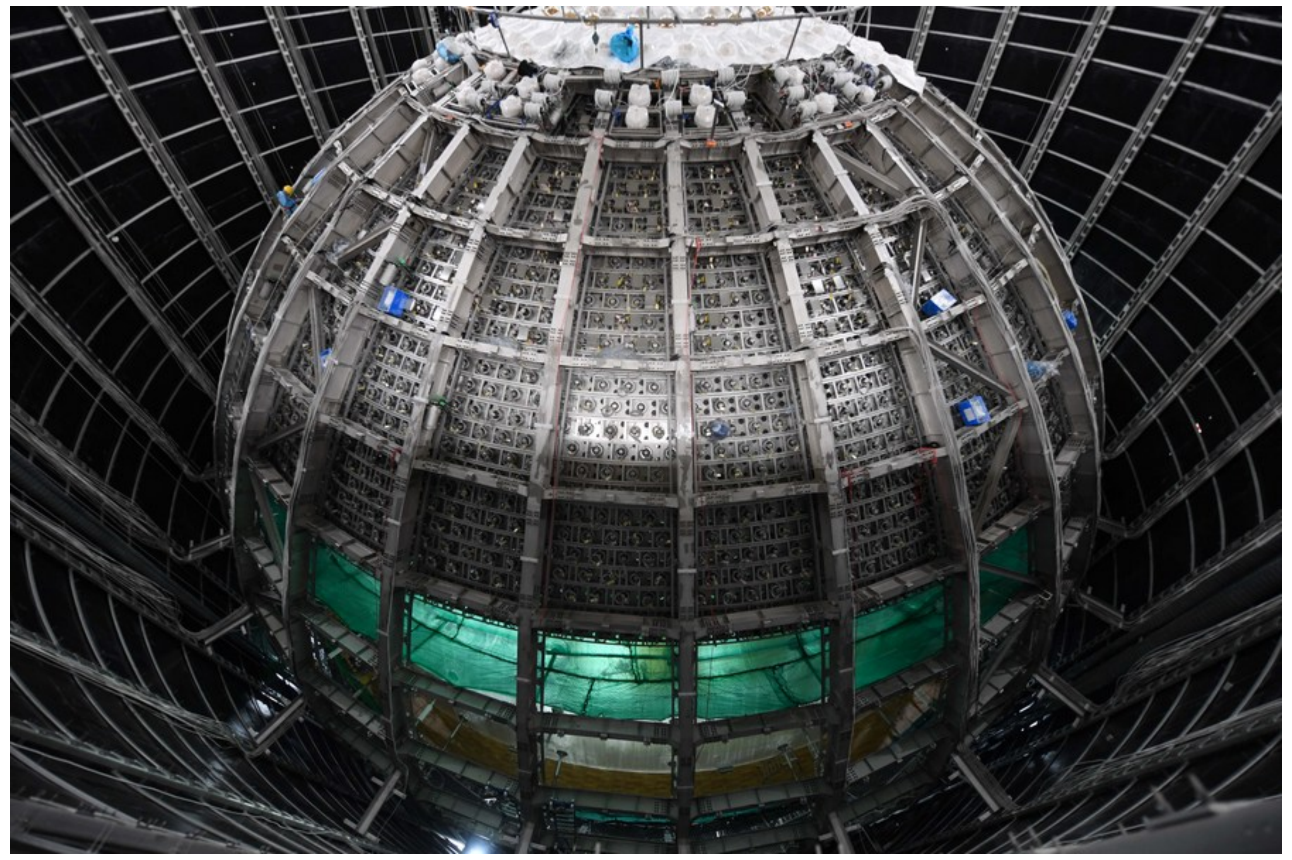
? Hyper-K



FV 22.5 kton
ntag eff ~70% (w/ 0.033% Gd)

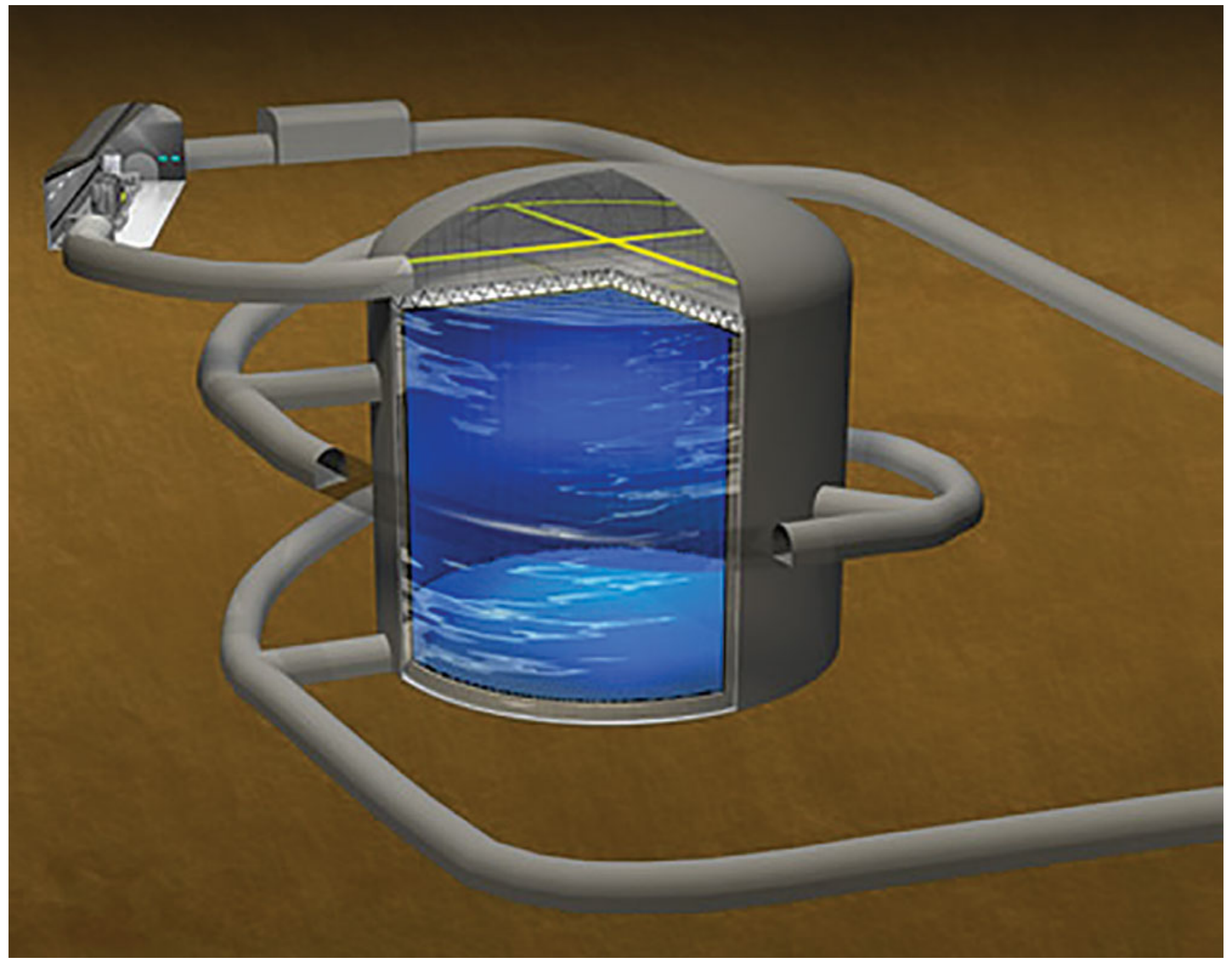


FV ~0.5 kton
ntag eff >90%



FV ~17 kton
ntag eff >90%

FV ~189 kton
ntag eff ? (ref. ~20% at SK pure water)



Pros & Cons

- **Super-K, KamLAND**

  Stably running for a long time (~ large statistics data are already there)

  No big statistical jump expected until its end

- **JUNO**

  High ntag efficiency hence a lower energy threshold (~10 MeV)

  Potentially fewer spallation background due to the more limited chain than oxygen

  Well-measured neutrino cross sections on carbon

  Smaller statistics in the next generation (realistic reach up to **~30 MeV**)

- **Hyper-K**

  Overwhelmingly larger statistics to be achieved

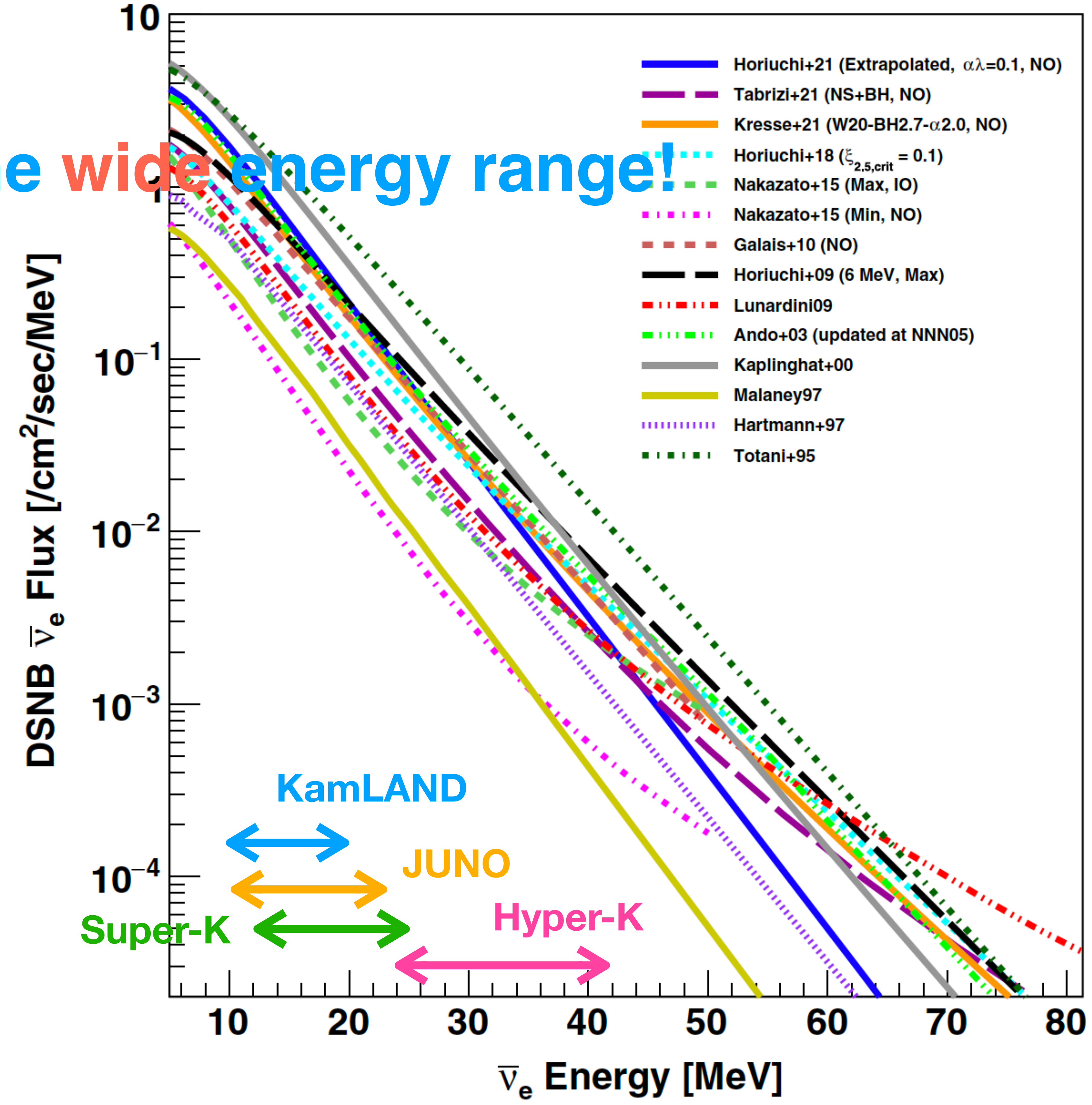
  Lower ntag efficiency

  Huge amount of muon spallation background due to a shallow overburden (hard at **<~24 MeV**)

Take Away from Experiment Side

- 10~24 MeV at Super-K, KamLAND, JUNO; >~24 MeV at Hyper-K (some efforts can improve this!)
- Combining data from different experiments would benefit not only statistics, but also constraint of common background systematics.

➡ **Important to measure the DSNB flux over the wide energy range!**



A New Tool: CARNE

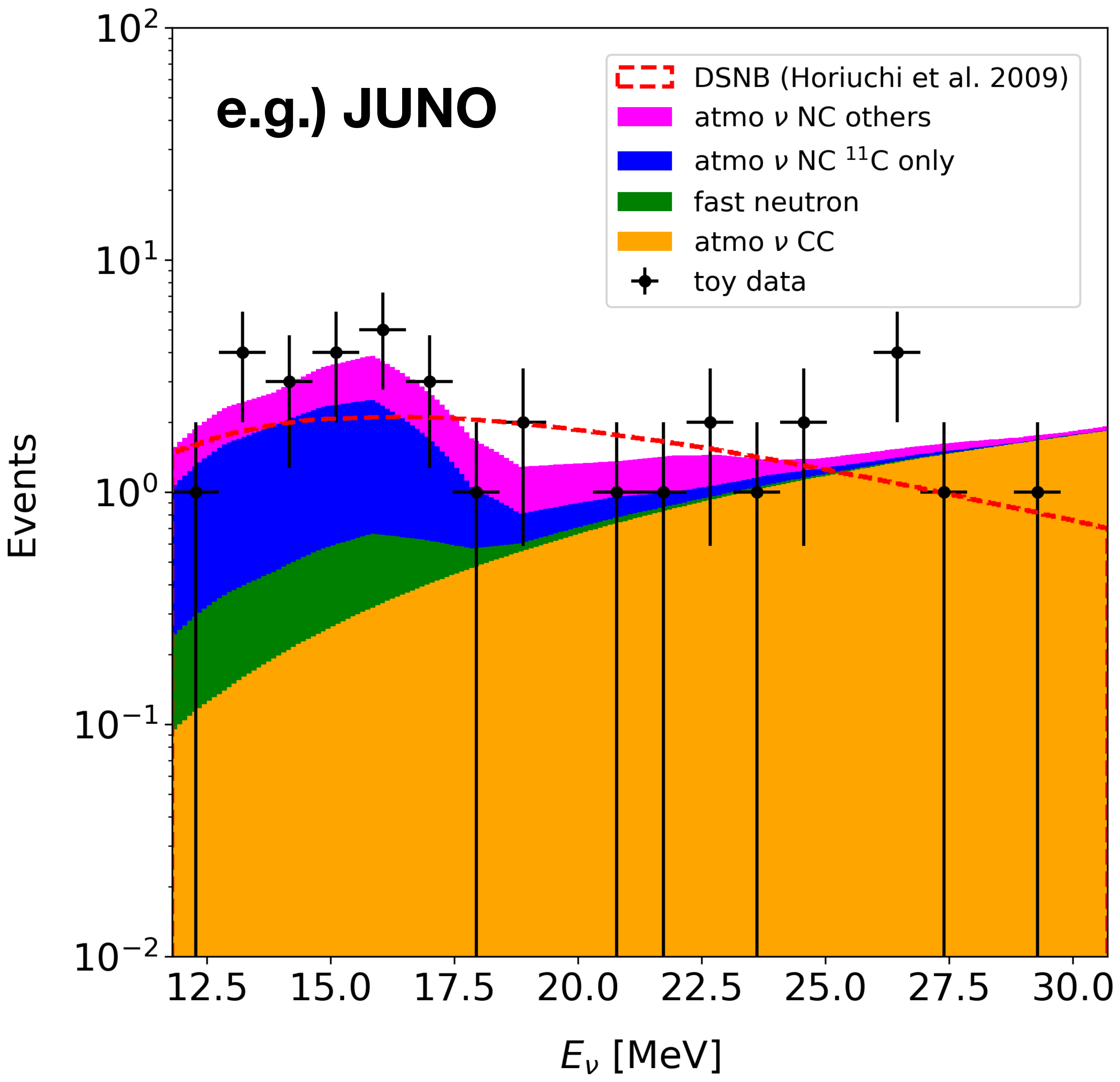
- Now developing a new package to calculate sensitivity of an experiment to a certain model.
  - CARNE: **C**ode for **A**nalyzing **R**elic **NE**utrinos
  - *For theorists*: a tool for testing their own models
  - *For experimentalists*: basis for the future collaboration among experiments

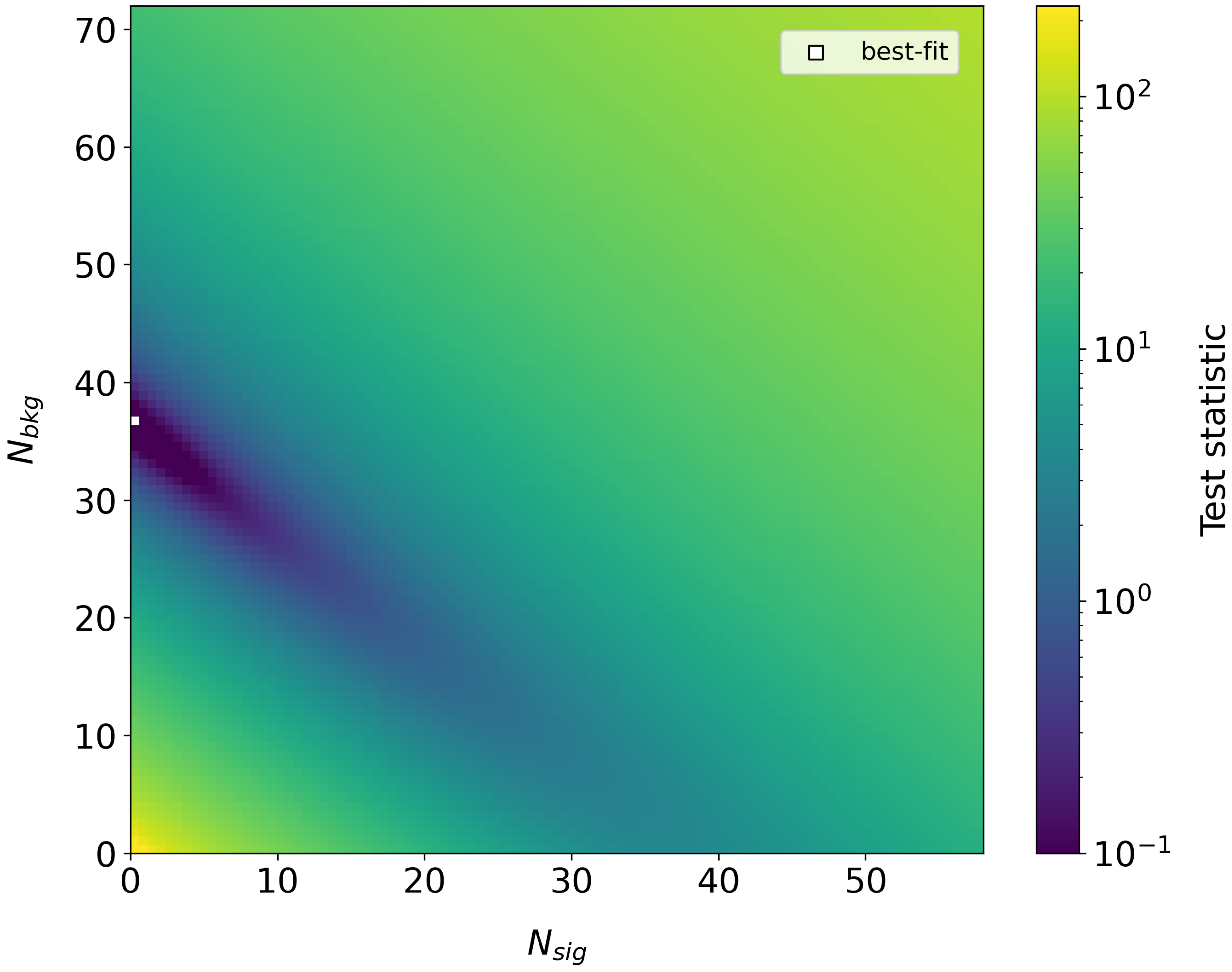
- Strategy & Goals
  - Statistical model: an extended maximum unbinned likelihood method
  - Basic scheme to be provided based on released signal & background PDFs from experiments

A New Tool: CARNE

- Now developing a new package to calculate sensitivity of an experiment to a certain model.
  - **CARNE**: **C**ode for **A**nalyzing **R**elic **NE**utrinos
  - *For theorists*: a tool for testing their own models
  - *For experimentalists*: basis for the future collaboration among experiments

- Strate
  - St m unbinned
  - Ba released s



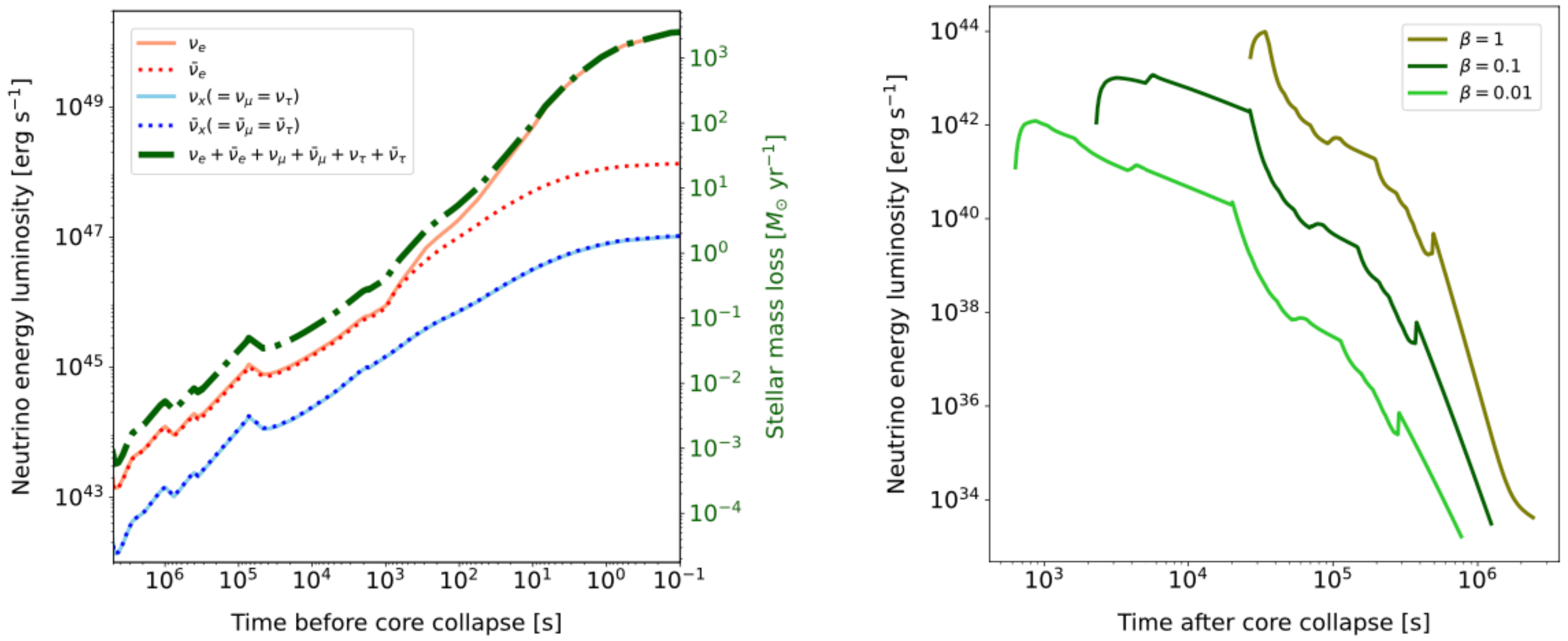


JUNO

Summary

- **DSNB** will be an important probe of astrophysics in the upcoming decade.
- Model assumptions can be reflected as a characteristic flux shape in the wide energy range.
- To maximize the experimental data, a combined analysis will be needed, bridging low and high energies.
- We started a new code development, **CARNE**, to achieve these demands, planning a release on GitHub.

ads: another “multi” energy neutrino study



Towards Multi Energy Neutrino Astronomy:
Diagnosing Enhanced Circumstellar Material around Stripped-Envelope Supernovae

Ryo Sawada[1,*] and Yosuke Ashida[2,3,*]

[1] Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan
[2] Department of Physics, Kyoto University, Kyoto, Kyoto 606-8502, Japan
[3] Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah 84112, USA

accepted by ApJ

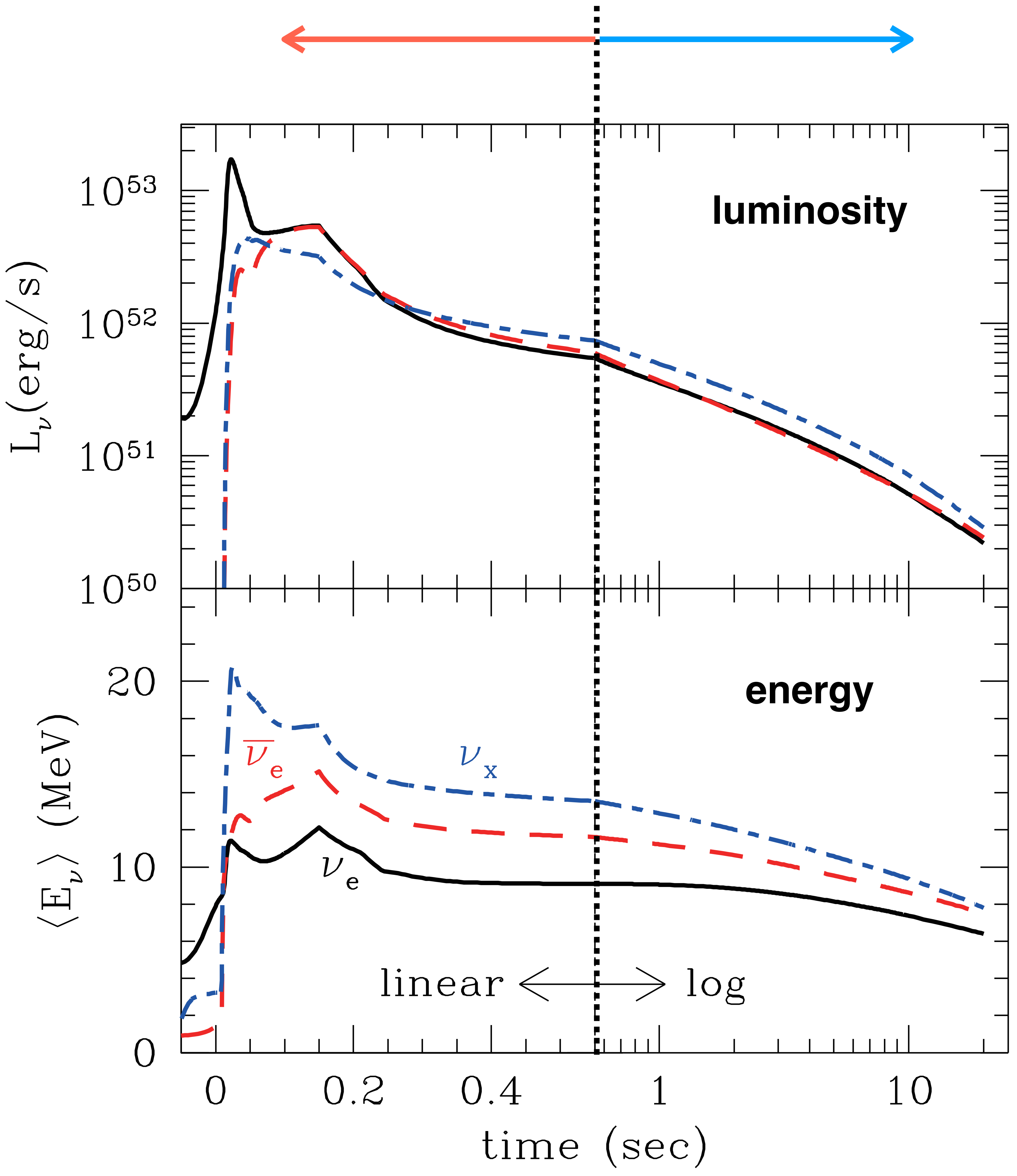
Supplements

Neutrino Emission in Collapse Process

K. Nakazato et al., ApJ Suppl. 205, 2 (2013)

accretion phase

- Both **NS** and **BH** cases
- Longer accretion for BH case
- Mainly ν_e and anti-ν_e
- Higher energy



cooling phase

- Only **NS** case
- Large integrated flux
- All flavors
- Lower energy

Diffuse Supernova Neutrino Background

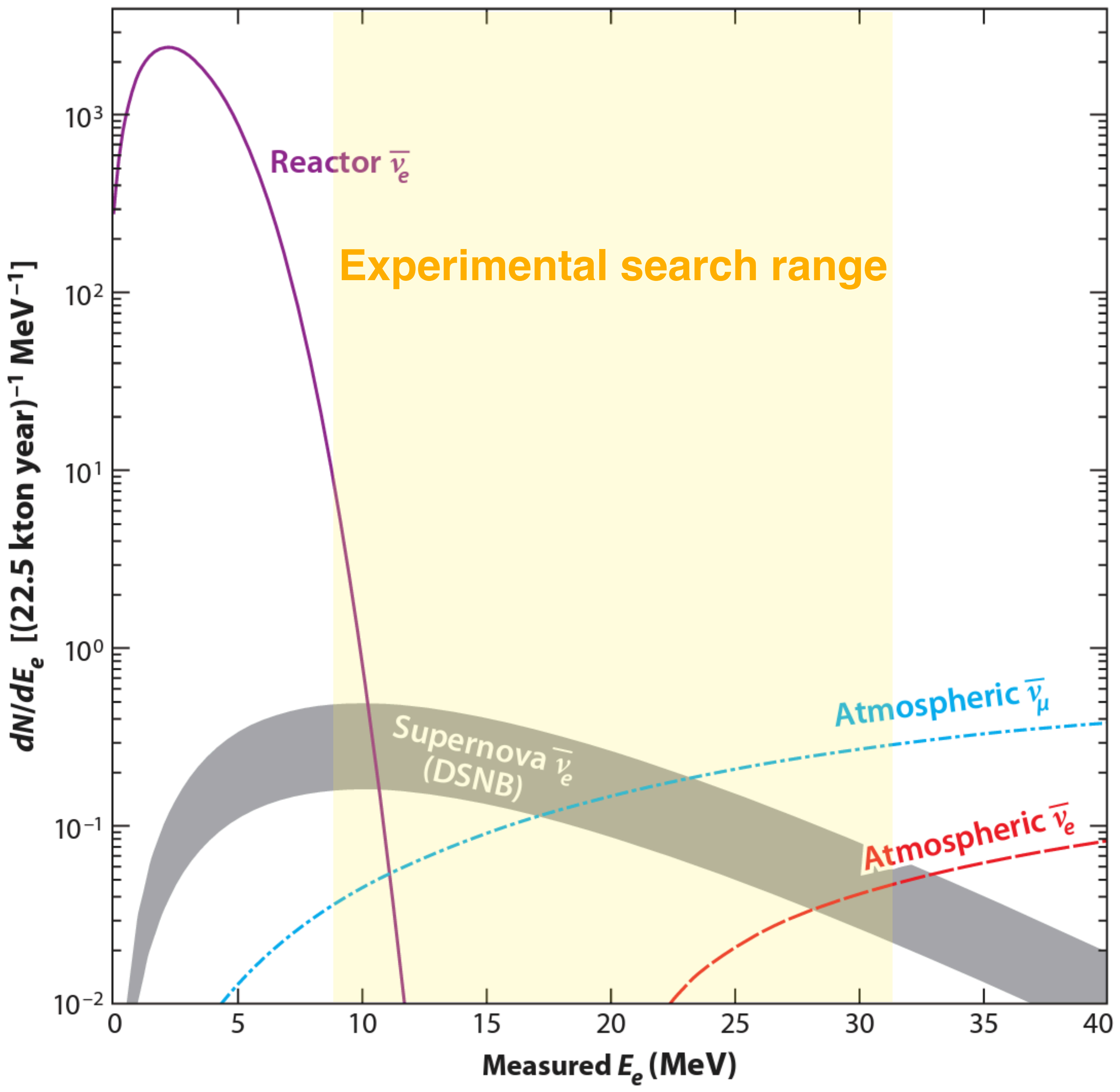
The accumulated flux of neutrinos from all past core collapses over the cosmic history

= **Diffuse Supernova Neutrino Background** (DSNB)

- Many factors affecting DSNB (SFR, nuclear EOS, BH formation, neutrino oscillation, etc).
- Experimental detection is challenging because of small flux & huge backgrounds.

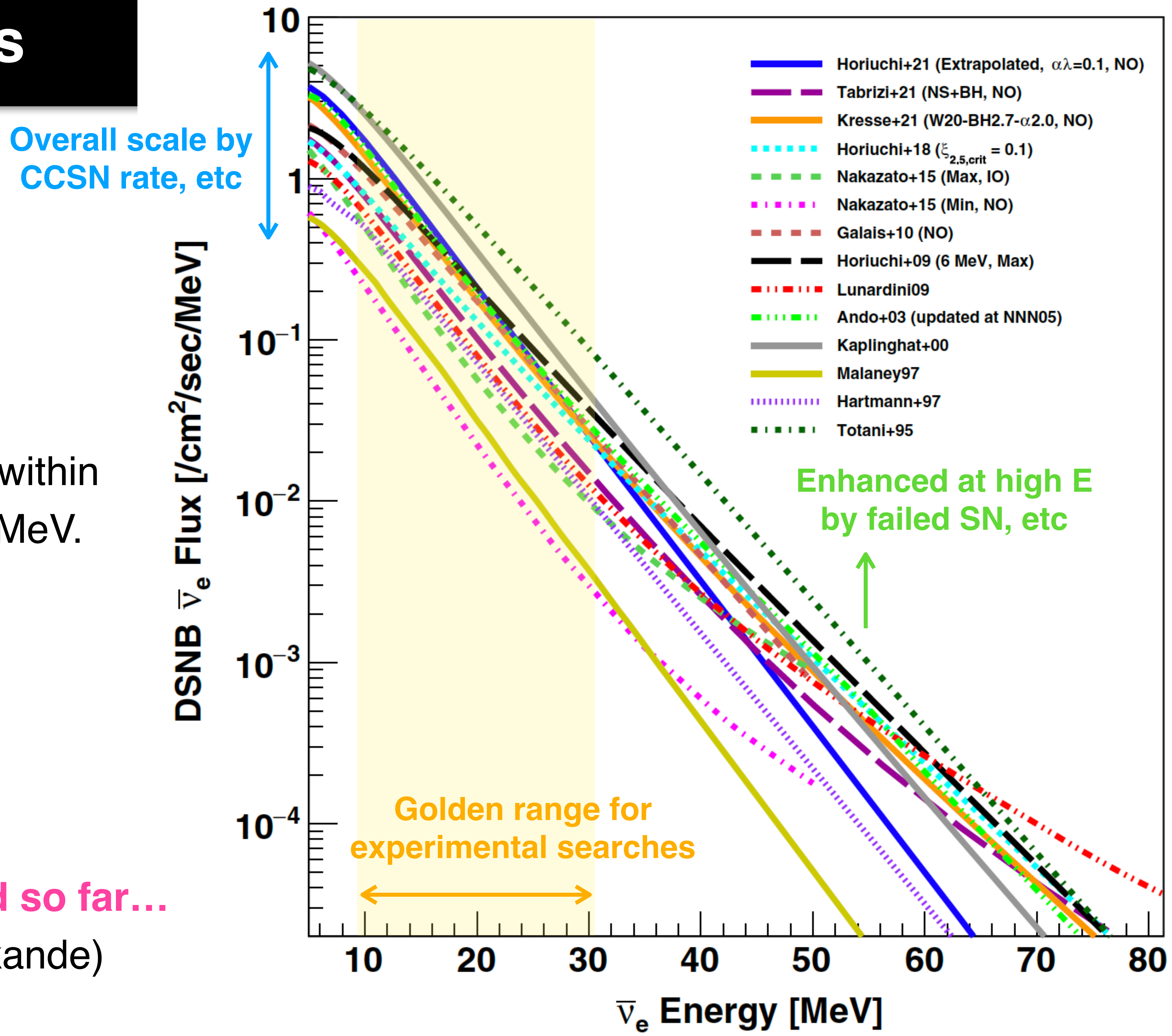
$$\Phi = \int [\nu \text{ emission}] \otimes [\text{Star formation}] \otimes [\text{Universe expansion}]$$

J. F. Beacom, ARNPS 60, 439 (2010)



DSNB Flux Predictions

Most theoretical predictions exist within ~1 order of magnitude at 10~30 MeV.



Not experimentally discovered so far…

(best limits by Super-Kamiokande)

Mass Hierarchy Impact

$$\begin{aligned}
\frac{dN_{\bar{\nu}_e}}{dE_\nu} &= |U_{e1}|^2 \frac{dN_{\bar{\nu}_1}}{dE_\nu} + |U_{e2}|^2 \frac{dN_{\bar{\nu}_2}}{dE_\nu} + |U_{e3}|^2 \frac{dN_{\bar{\nu}_3}}{dE_\nu} \\
&= \cos^2\theta_{12}\cos^2\theta_{13} \frac{dN_{\bar{\nu}_1}}{dE_\nu} + \sin^2\theta_{12}\cos^2\theta_{13} \frac{dN_{\bar{\nu}_2}}{dE_\nu} + \sin^2\theta_{13} \frac{dN_{\bar{\nu}_3}}{dE_\nu} \\
&\sim 0.68 \cdot \frac{dN_{\bar{\nu}_1}}{dE_\nu} + 0.30 \cdot \frac{dN_{\bar{\nu}_2}}{dE_\nu} + 0.02 \cdot \frac{dN_{\bar{\nu}_3}}{dE_\nu},
\end{aligned}$$

$$\Rightarrow \quad \frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim 0.68 \cdot \frac{dN^0_{\bar{\nu}_e}}{dE_\nu} + 0.32 \cdot \frac{dN^0_{\bar{\nu}_x}}{dE_\nu}.$$

Normal: All flavors

$$\Rightarrow \quad \frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim \frac{dN^0_{\bar{\nu}_x}}{dE_\nu}.$$

Inverted: NuMu+NuTau

Contributions from Different Redshifts

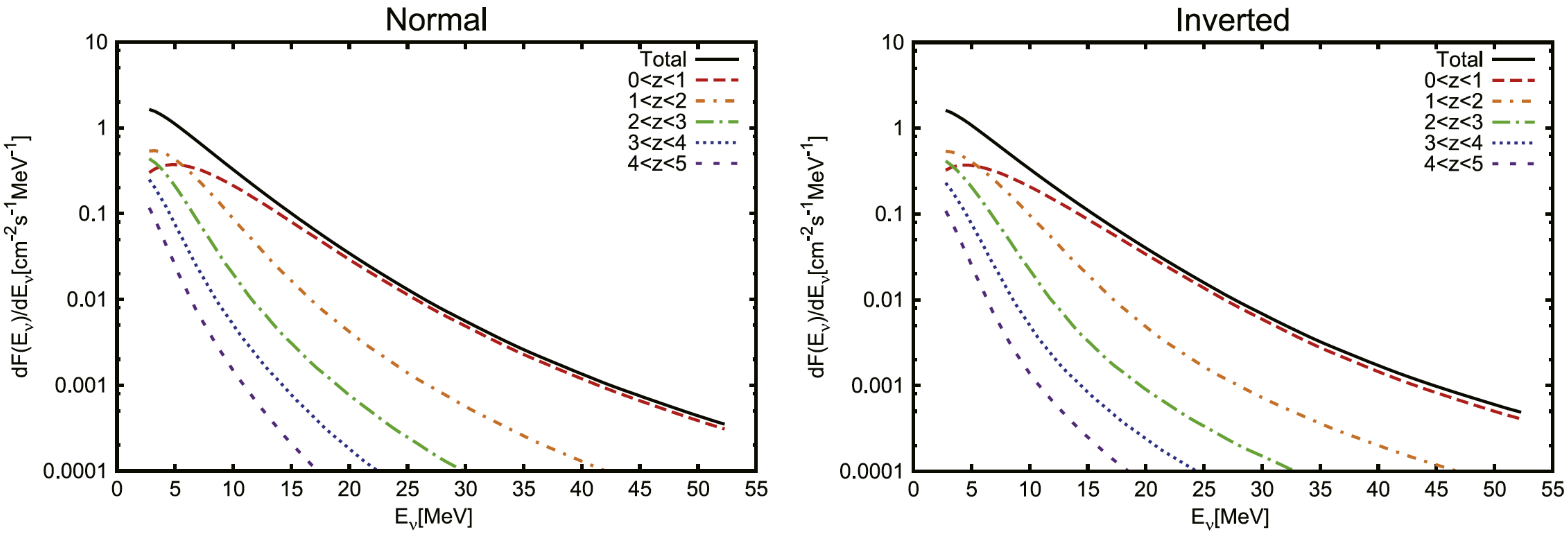


Figure 10. Total fluxes of SRNs (solid) and contributions from various redshift ranges for the reference model. The lines except for the solid line correspond, from top to bottom, to the redshift ranges $0 < z < 1, 1 < z < 2, 2 < z < 3, 3 < z < 4$, and $4 < z < 5$, for $E_\nu > 10$ MeV. The left and right panels show the cases for normal and inverted mass hierarchies, respectively.

K. Nakazato et al., ApJ 804, 75 (2015)

Nuclear EOS Impact (BH Formation Case)

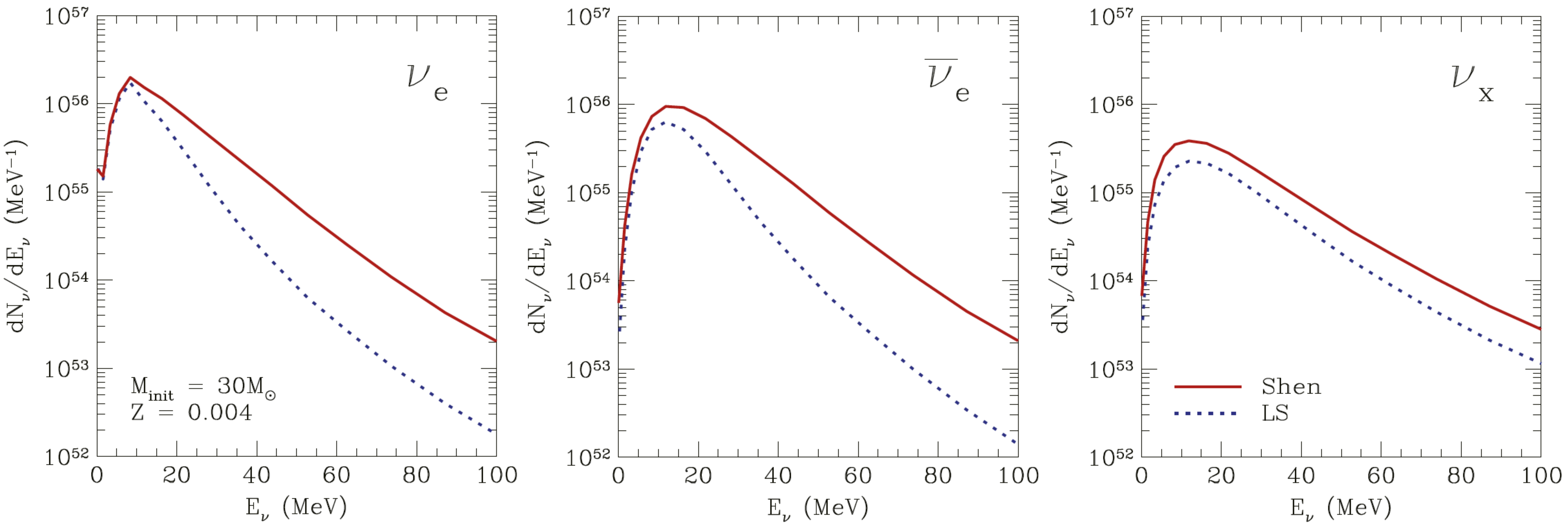
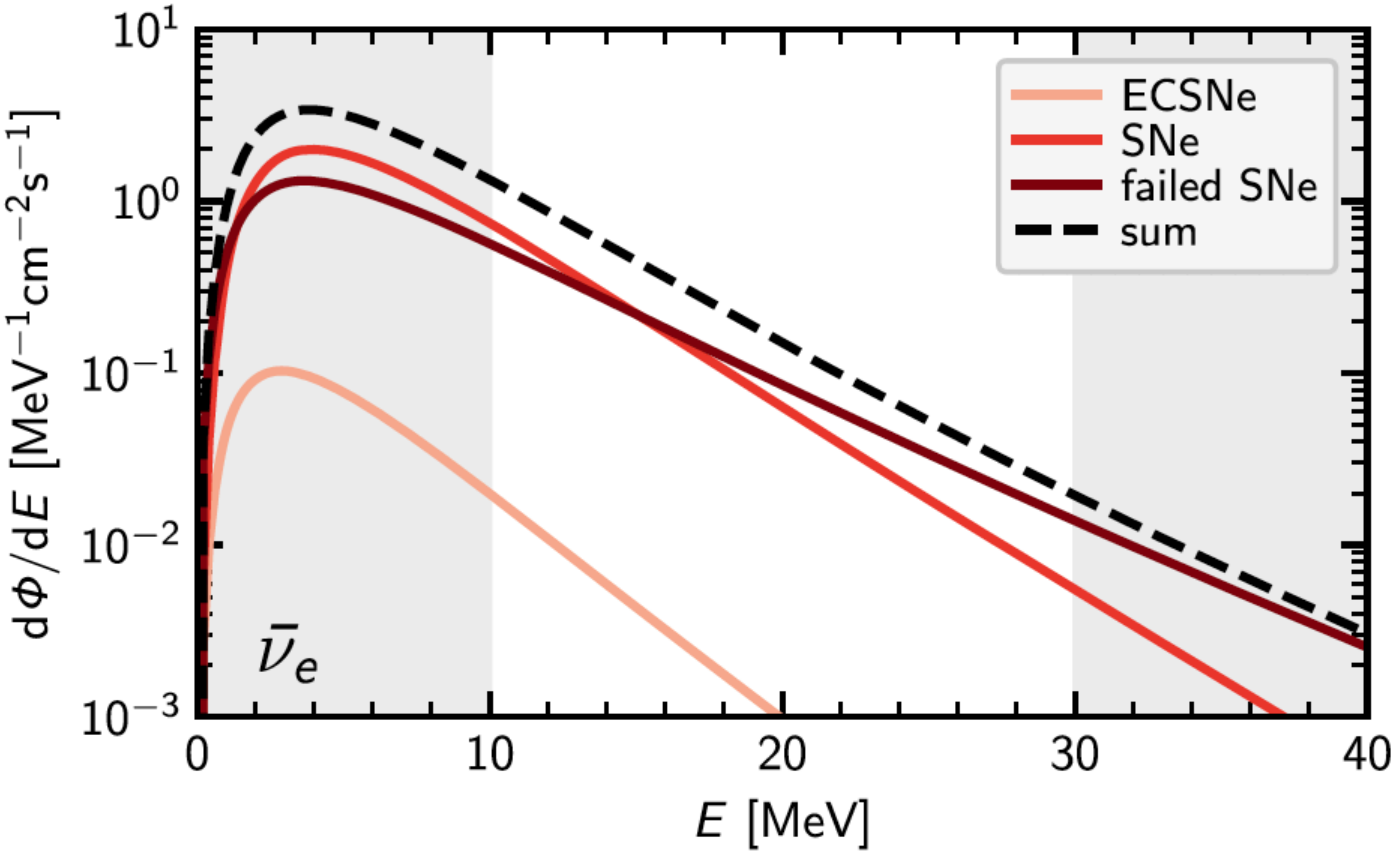


Figure 6. Neutrino number spectra for black hole formation with $30M_\odot$, $Z = 0.004$ and Shen EOS (solid) and LS EOS (dotted). The left, central, and right panels correspond to ν_e, $\bar{\nu}_e$, and ν_x $(=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau)$, respectively.

Shen is stiffer than LS (maximum mass of neutron stars is higher).

K. Nakazato et al., ApJ 804, 75 (2015)

Failed SN & Electron-Capture SN Contributions

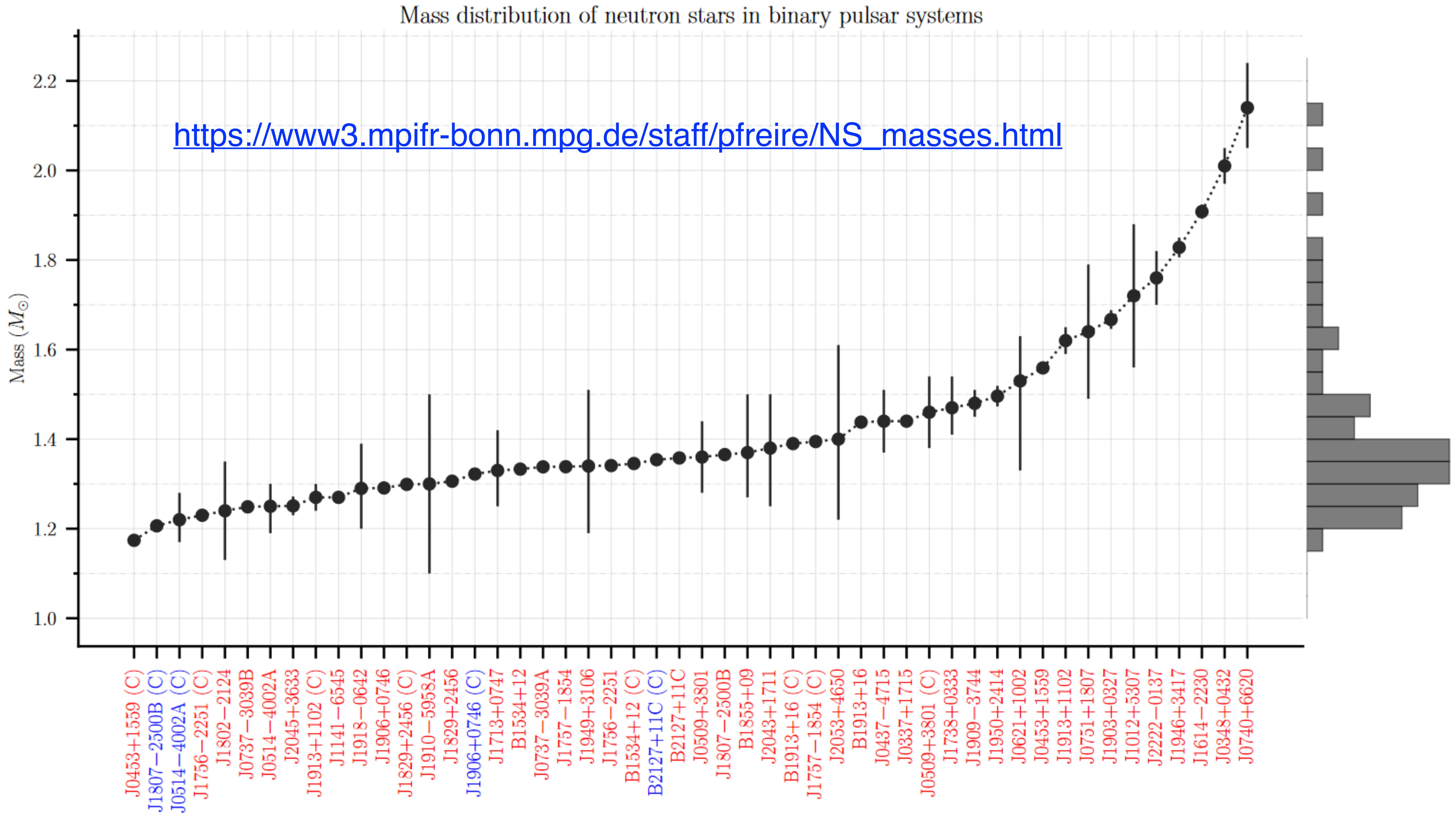


ECSNe = electron-capture supernovae
(marginal one around mass threshold, w/ ONeMg core)

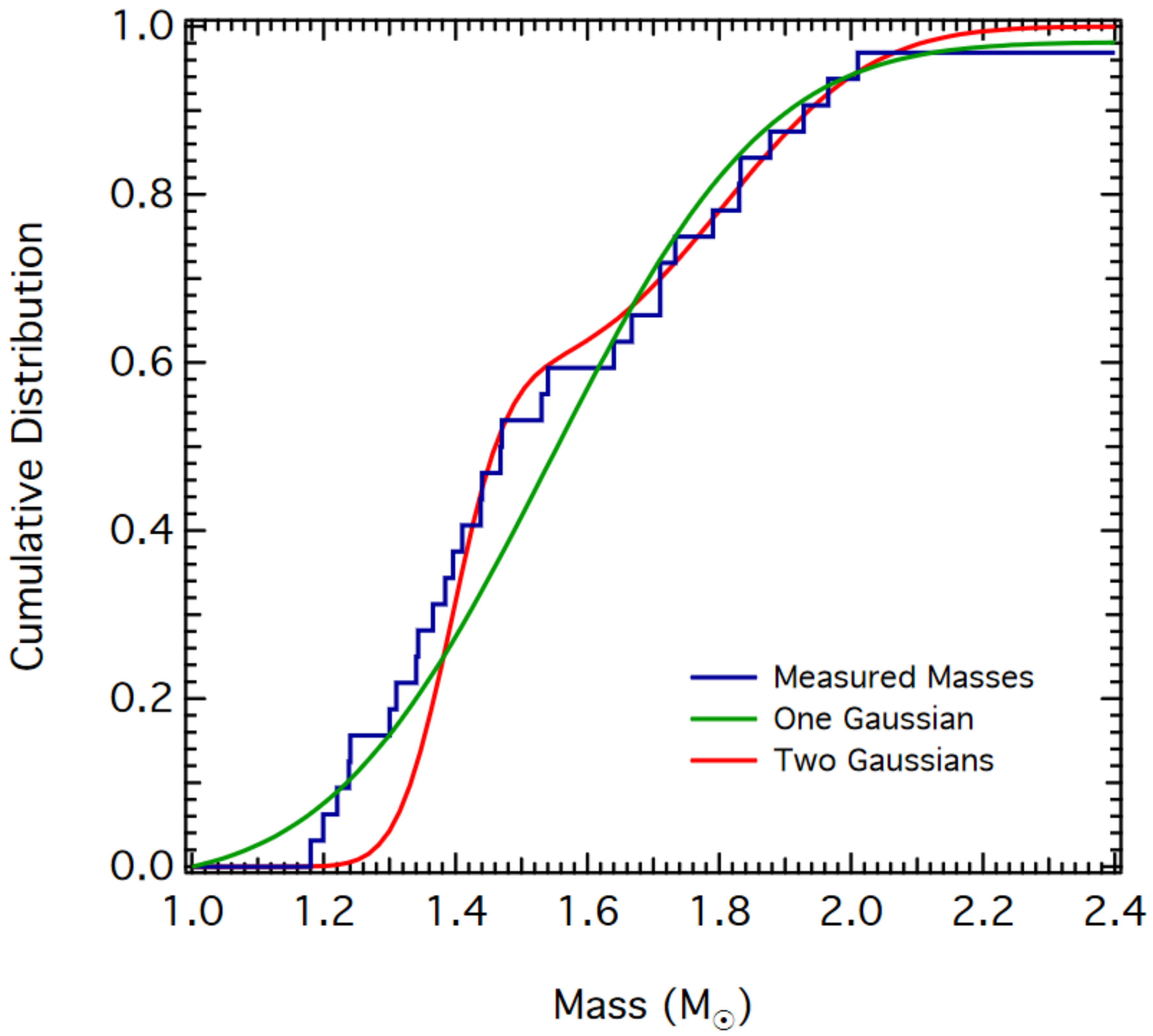
D. Kresse et al., ApJ 909, 169 (2021)

Ref: Observed Neutron Star Mass

- Neutron mass distribution from optical observations of the binary system shows a peak and higher tail.
- Natural born heavy, *or* gained mass through accretion from companion stars.



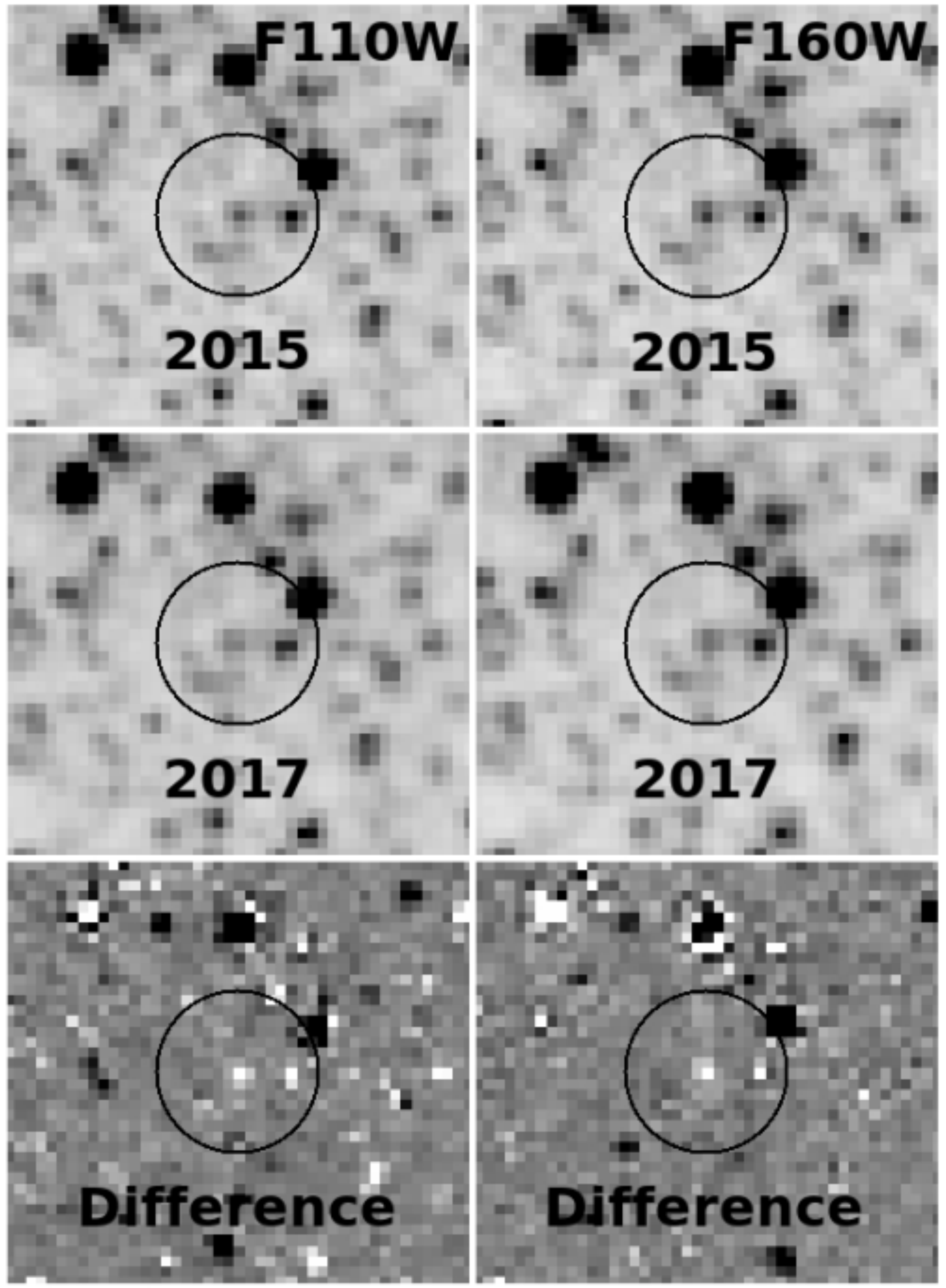
J. Antoniadis et al., arXiv:1605.01665



Ref: Failed SN Fraction

- Monitoring luminous stars gave constraints on a failed SN fraction.
- 2 failed SN candidates (N6946-BH1, M101-OC1) out of 8 SNe.
  - Failed SN fraction ~ **4–39% (90% C.L.)**, assuming $N_{FSN} = 1$ and $N_{SN} = 8$.

C. M. Basinger et al., arXiv:2007.15658



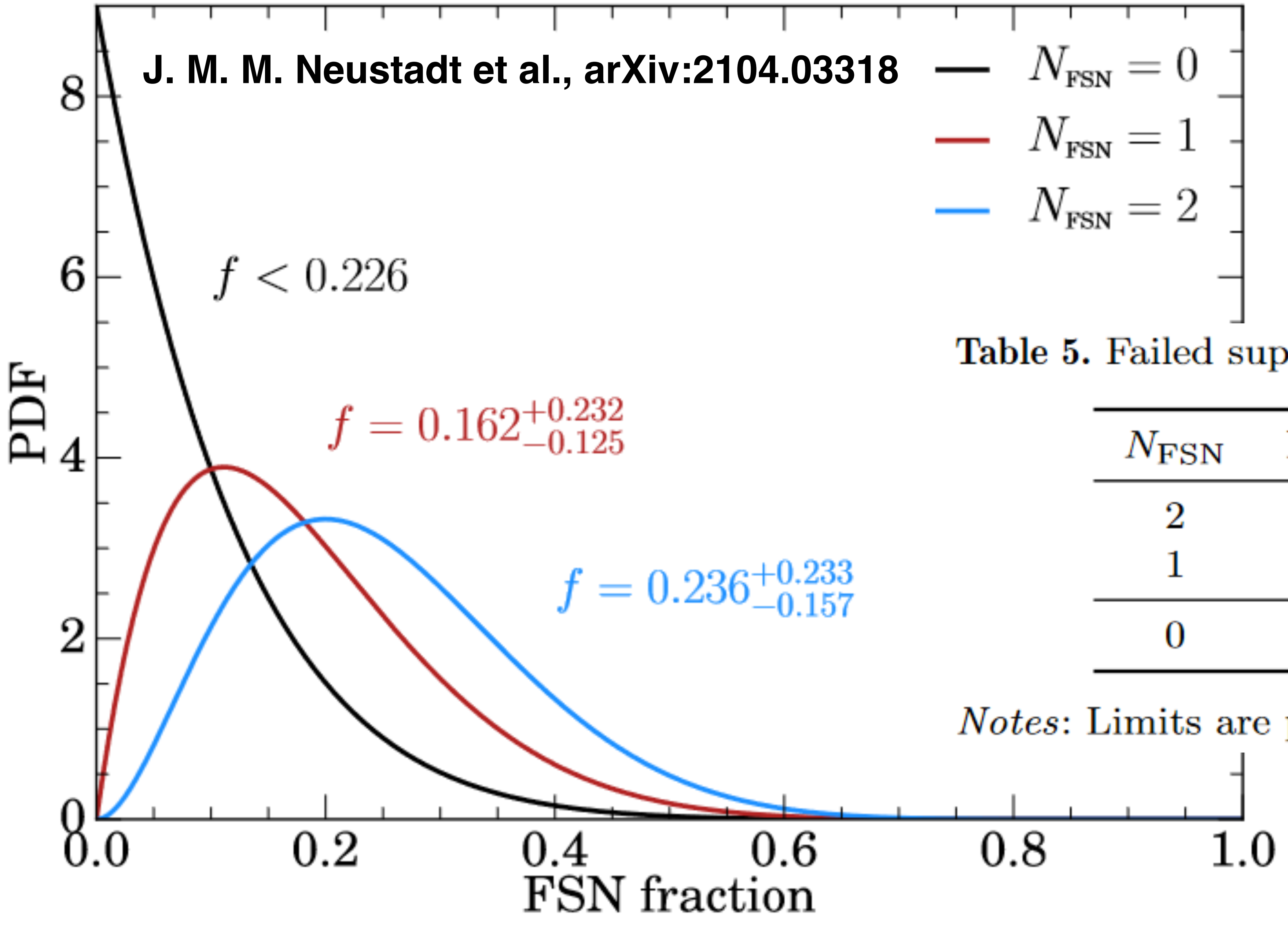


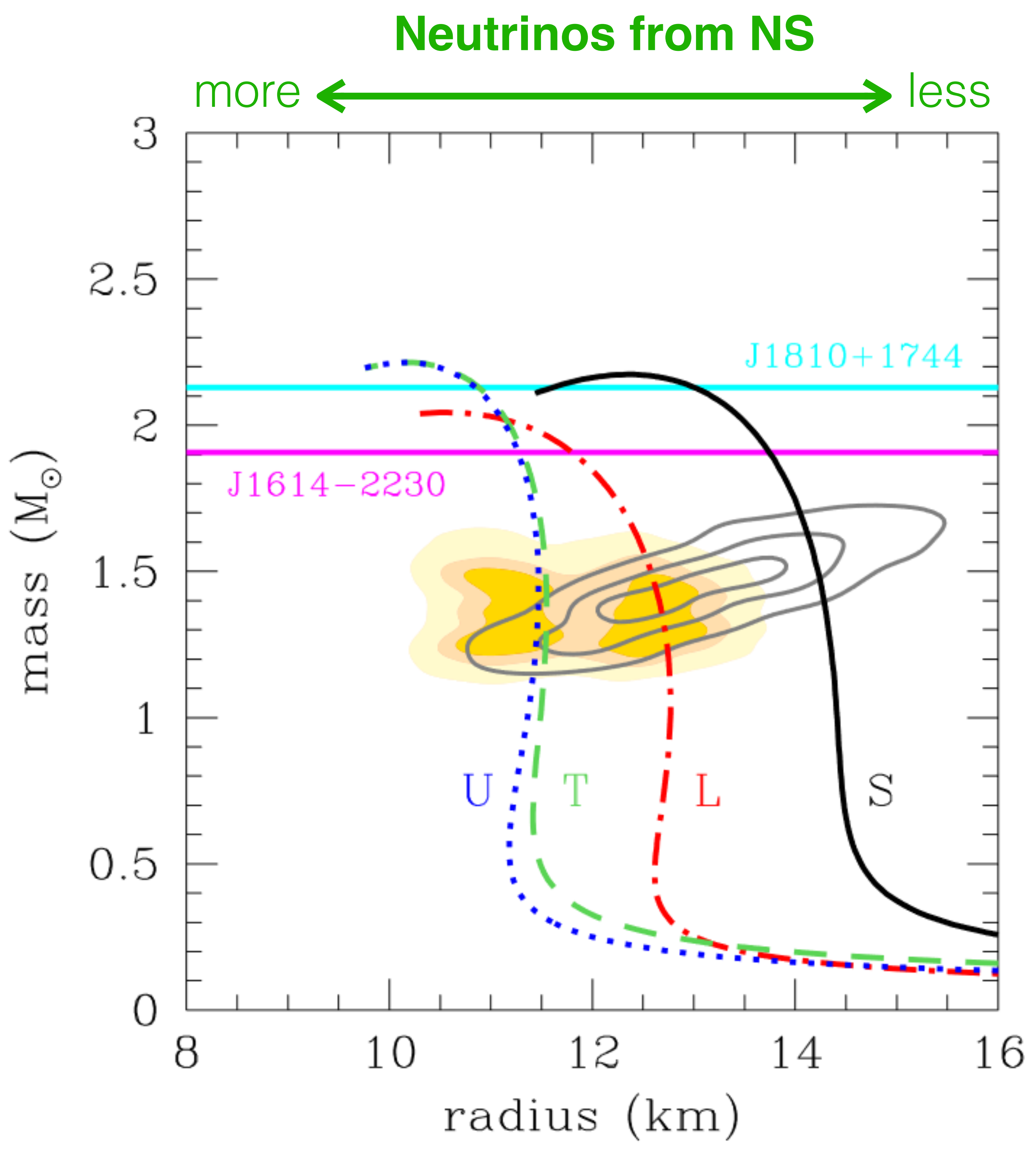
Table 5. Failed supernova/core-collapse fraction

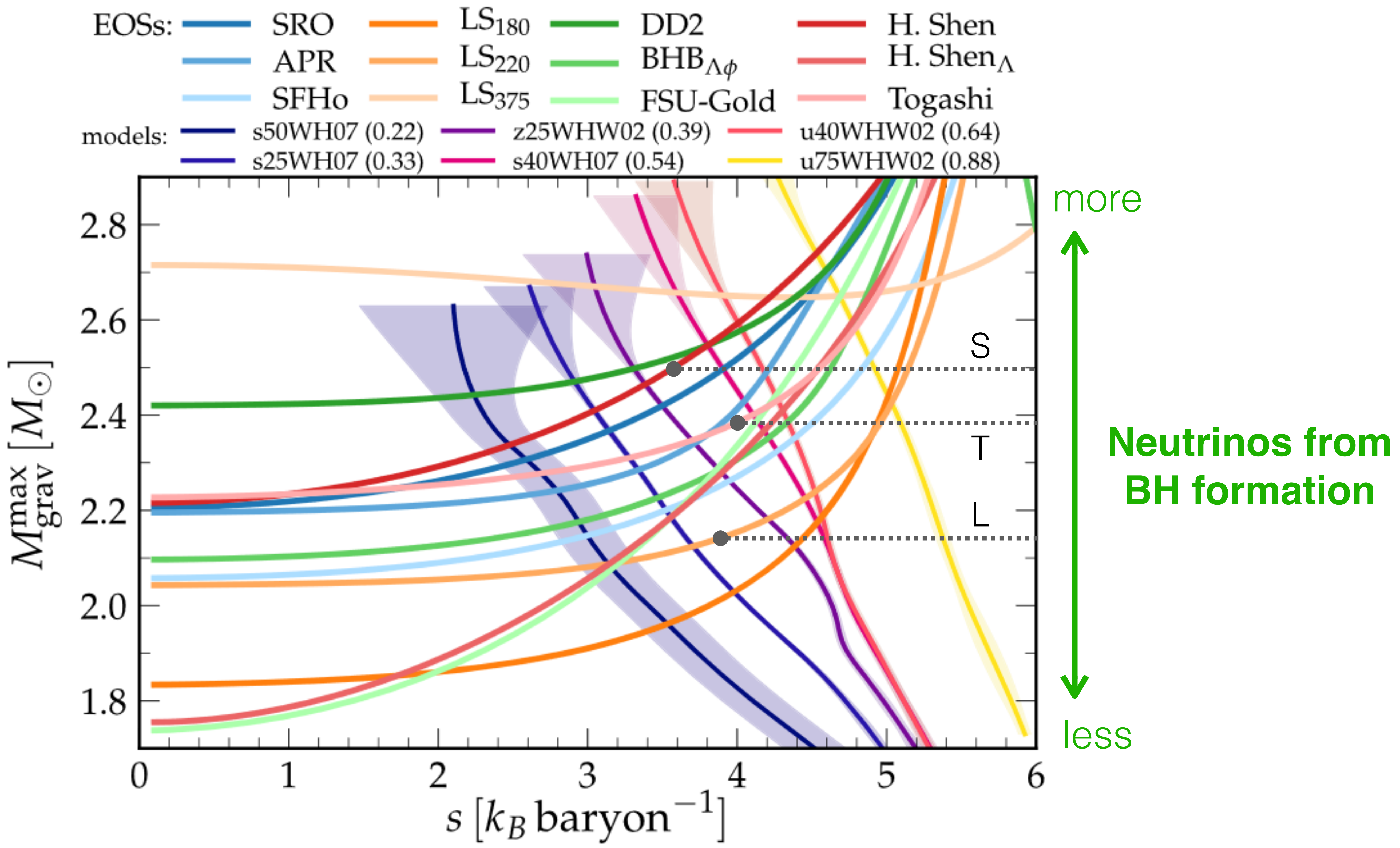
N_{FSN}	Lower limit	Median	Upper limit
2	0.079	0.236	0.470
1	0.037	0.162	0.394
0	–	–	0.226

Notes: Limits are presented at the 90 per cent confidence level.

Ref: Nuclear Equation-of-State Impact

- In the NS case, neutrino emission amount depends on ***radius*** of proto-NS.
- In the BH case, neutrino emission amount depends on ***maximum mass*** of proto-NS.

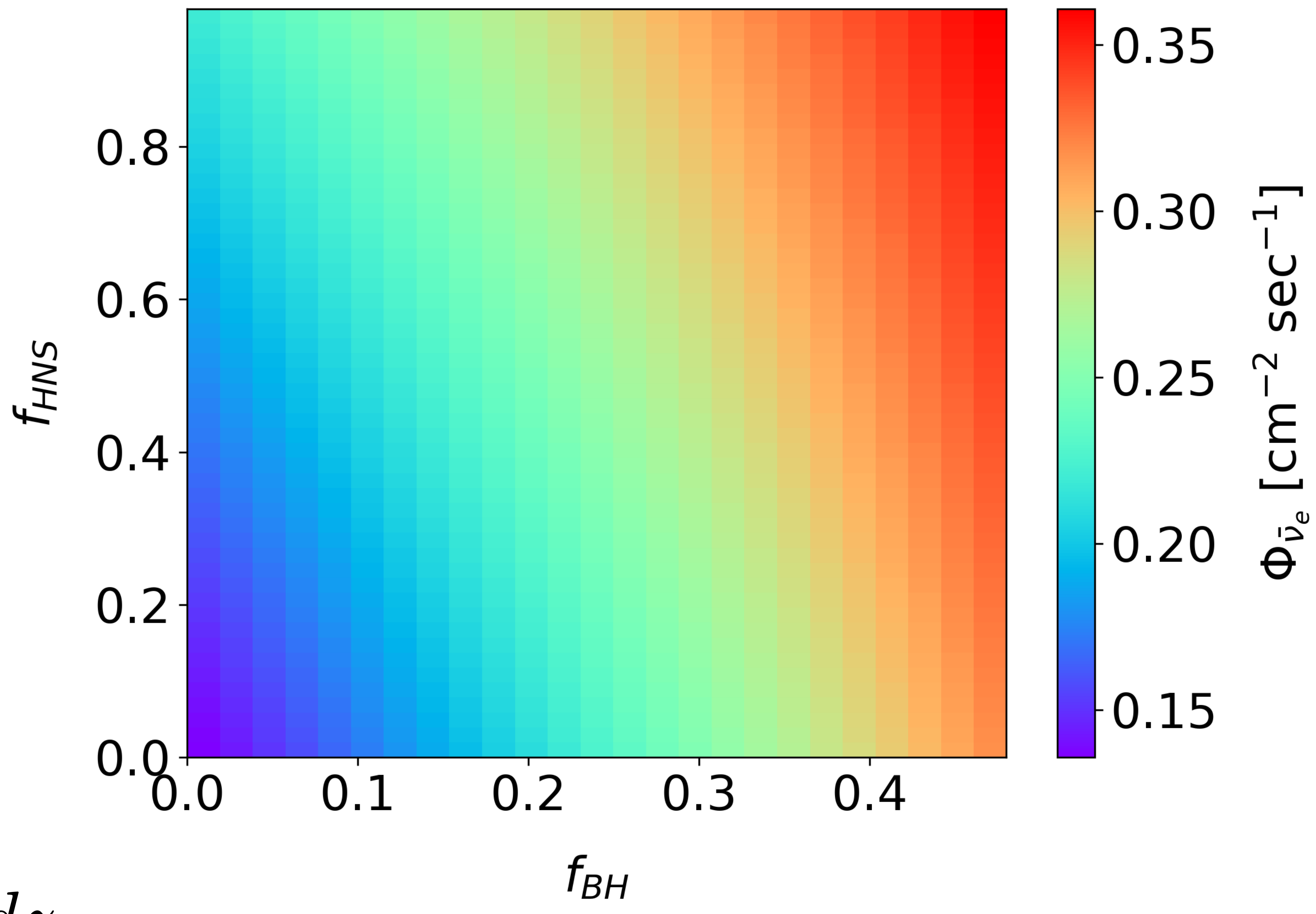




Mixture of Three Fluxes

- Mix three cases by fractional parameters, f_{HNS} and f_{BH}, to form a DSNB flux.
  - f_{BH}: fraction of BH to total core-collapse
  - f_{HNS}: fraction of high mass NS to total NS
- Integrated DSNB flux differs for $\{f_{\mathrm{HNS}}, f_{\mathrm{BH}}\}$ combinations.

(*Example*) Integrated DSNB flux for a certain energy range for different $\{f_{\mathrm{HNS}}, f_{\mathrm{BH}}\}$ combinations



DSNB flux at Earth

Neutrino spectrum from a core-collapse

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{CC}}(z)\boxed{\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle} \times \frac{dz}{H_0\sqrt{\Omega_{\mathrm{m}}(1+z)^3+\Omega_\Lambda}}$$

$$\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle = f_{\mathrm{BH}}\boxed{\frac{dN_{\mathrm{BH}}(E'_\nu)}{dE'_\nu}} + (1-f_{\mathrm{BH}}) \times \left[f_{\mathrm{HNS}}\boxed{\frac{dN_{\mathrm{HNS}}(E'_\nu)}{dE'_\nu}} + (1-f_{\mathrm{HNS}})\boxed{\frac{dN_{\mathrm{CNS}}(E'_\nu)}{dE'_\nu}} \right]$$

Experimental Sensitivity (2σ C.L.)

Detectable above lines

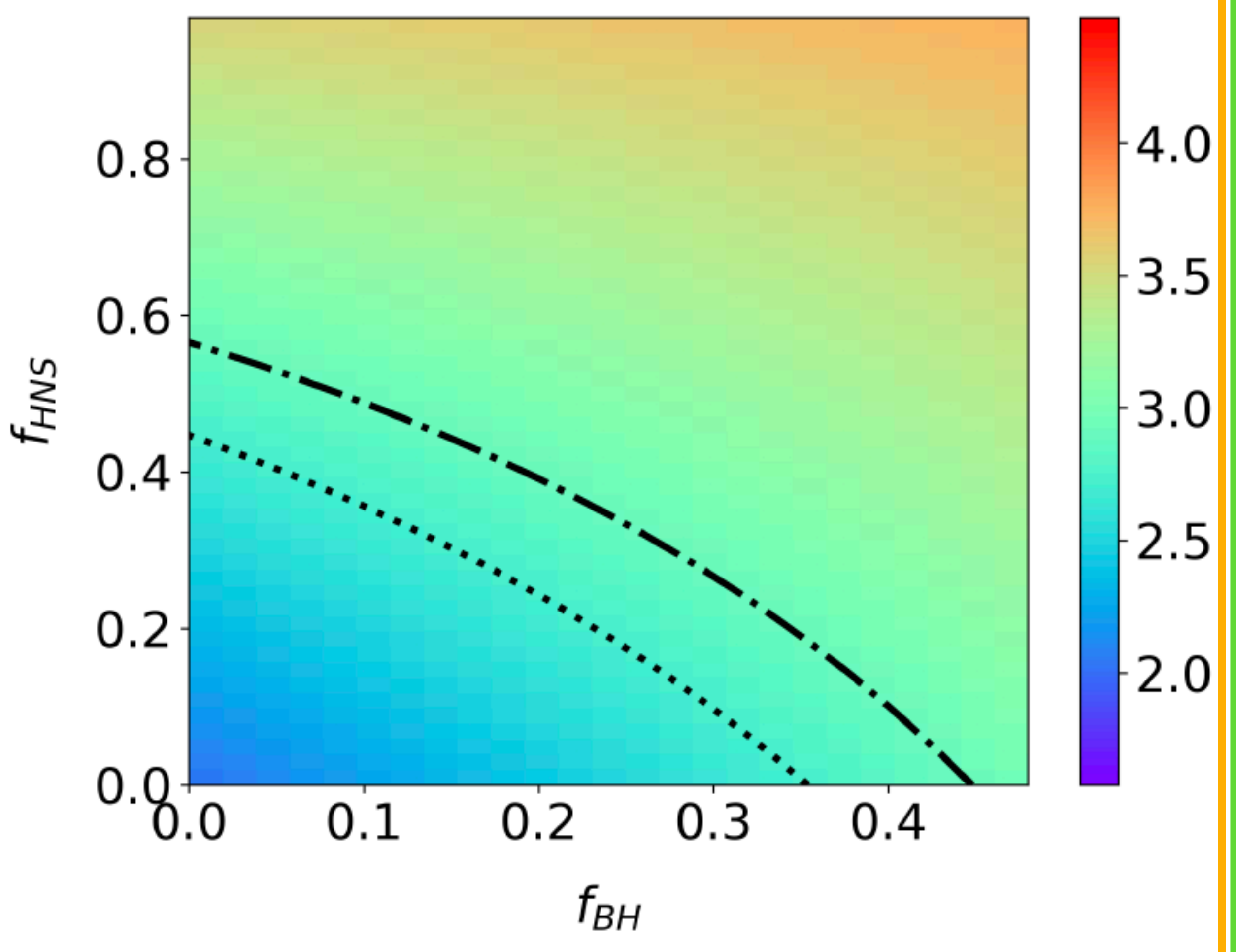
Normal mass ordering

Contours change for different EOSs.

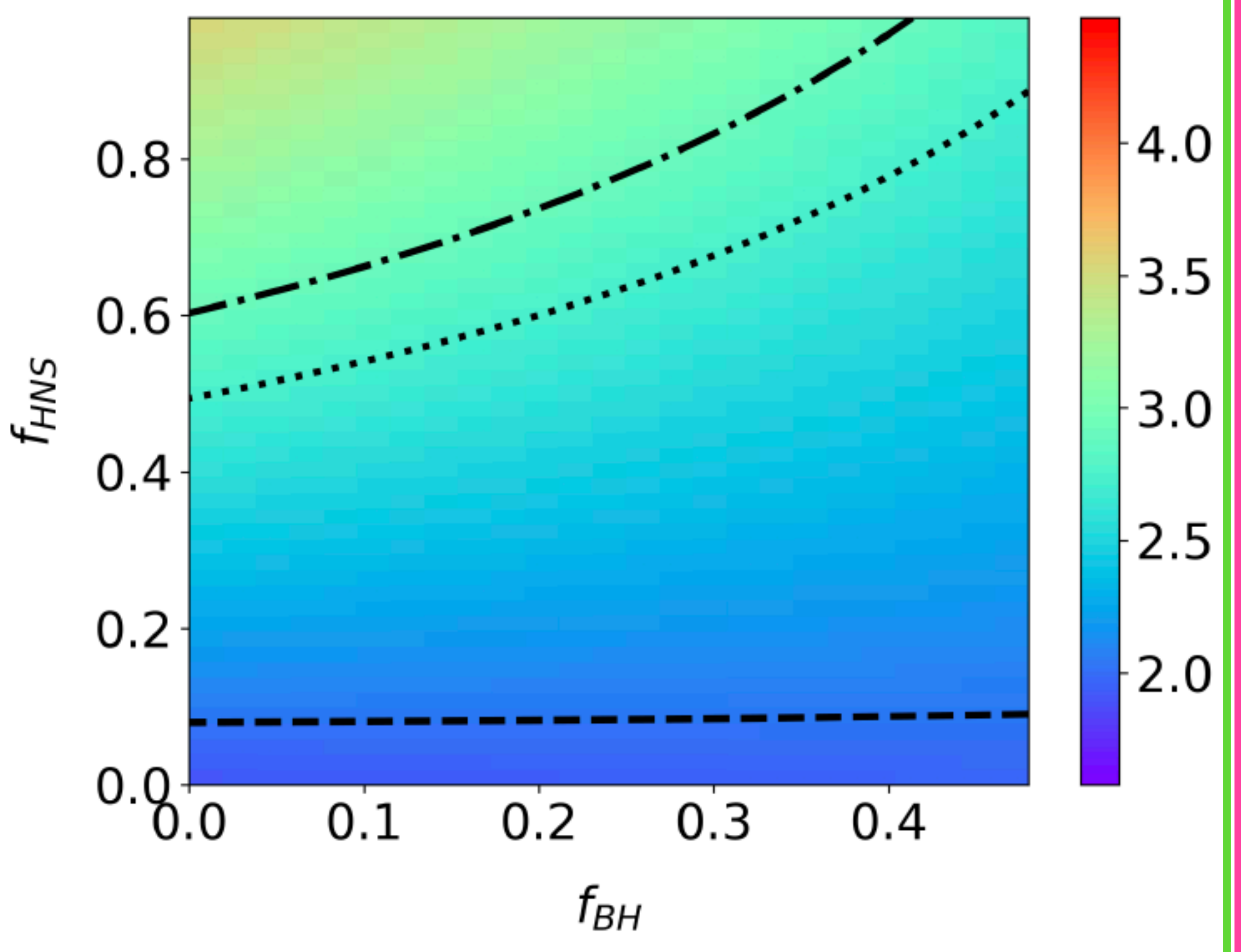
SK-Gd 10yr

Hyper-K 3yr

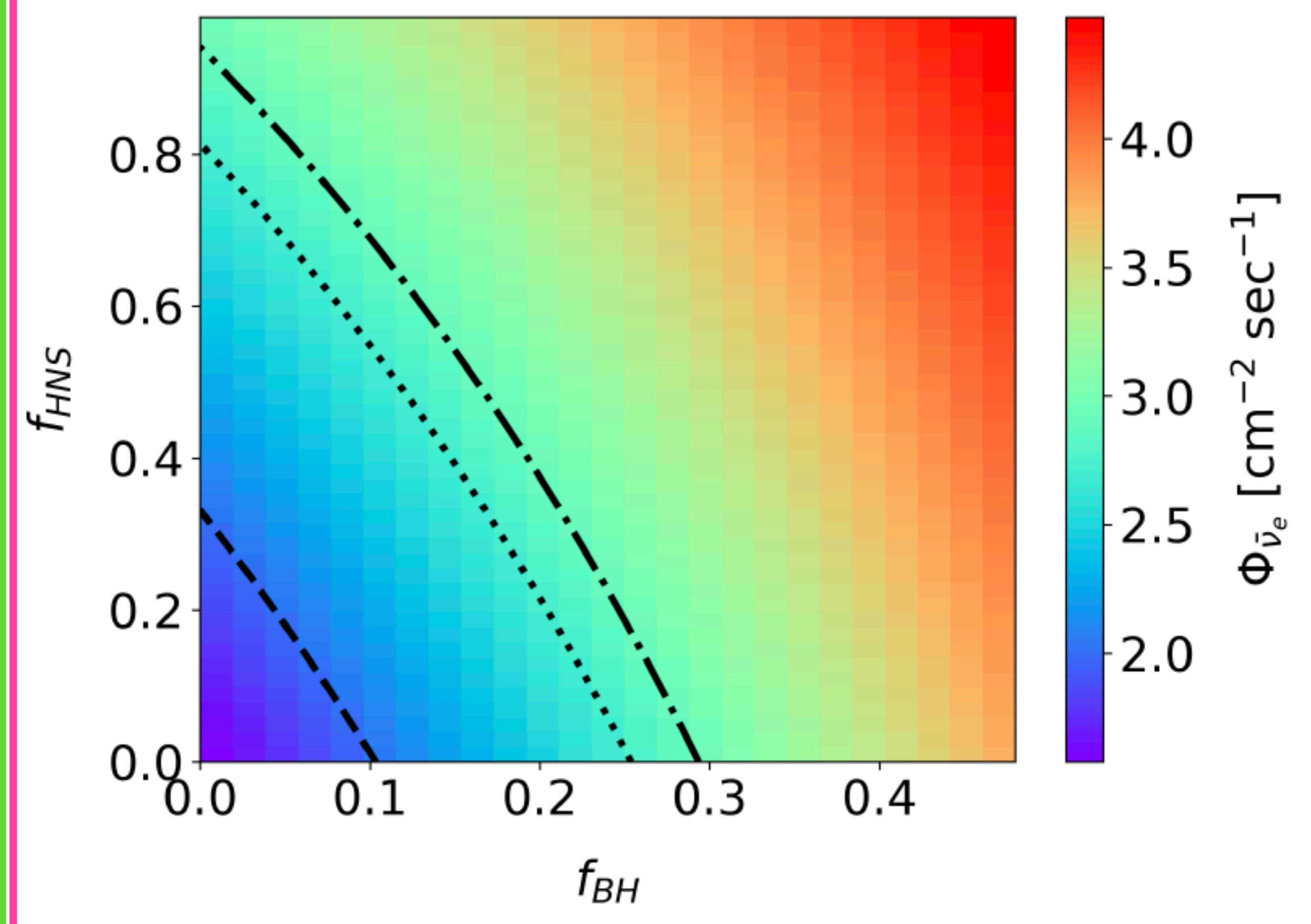
Hyper-K 5yr



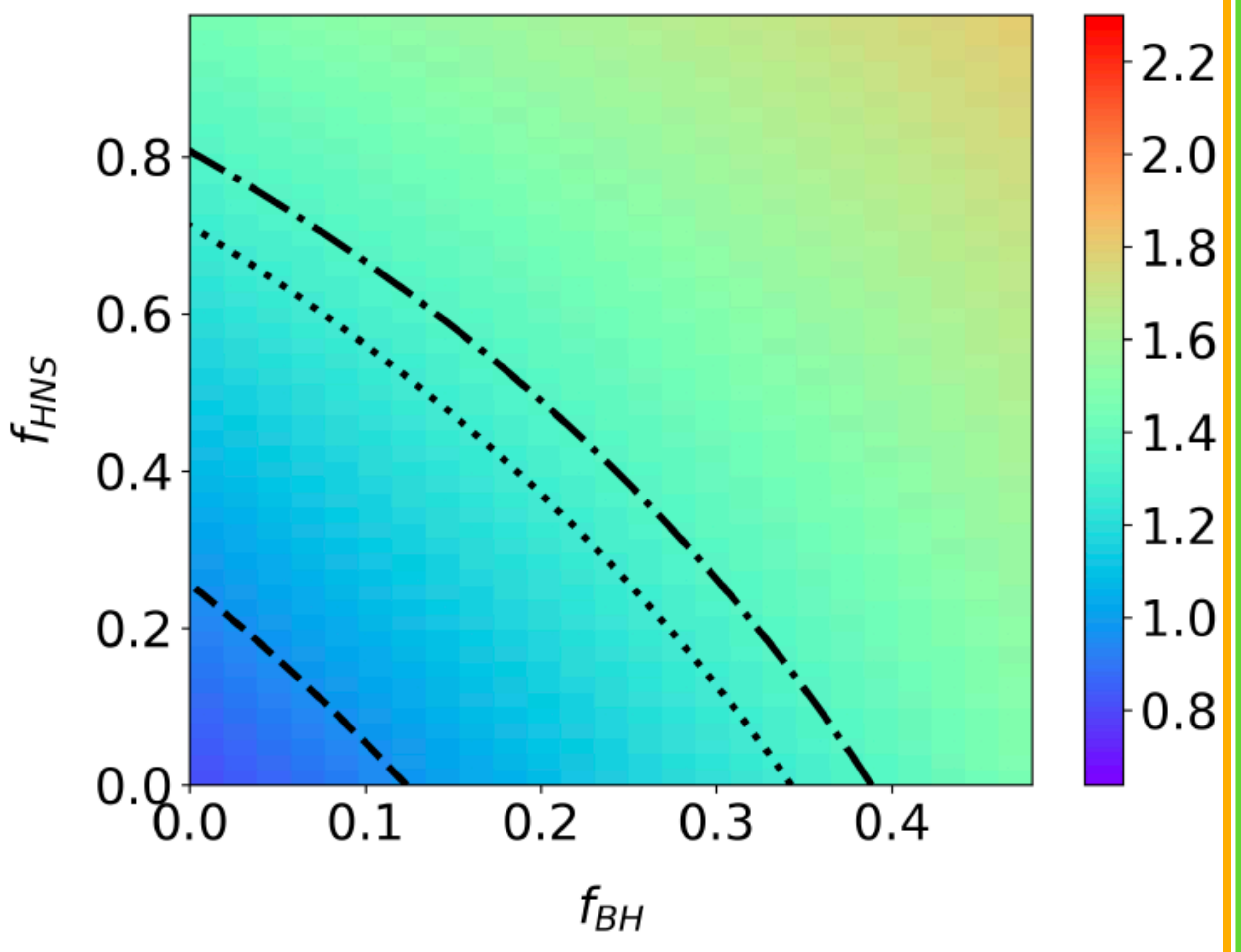
(1a) Togashi EOS, $13.3 < E_\nu < 31.3\,\mathrm{MeV}$



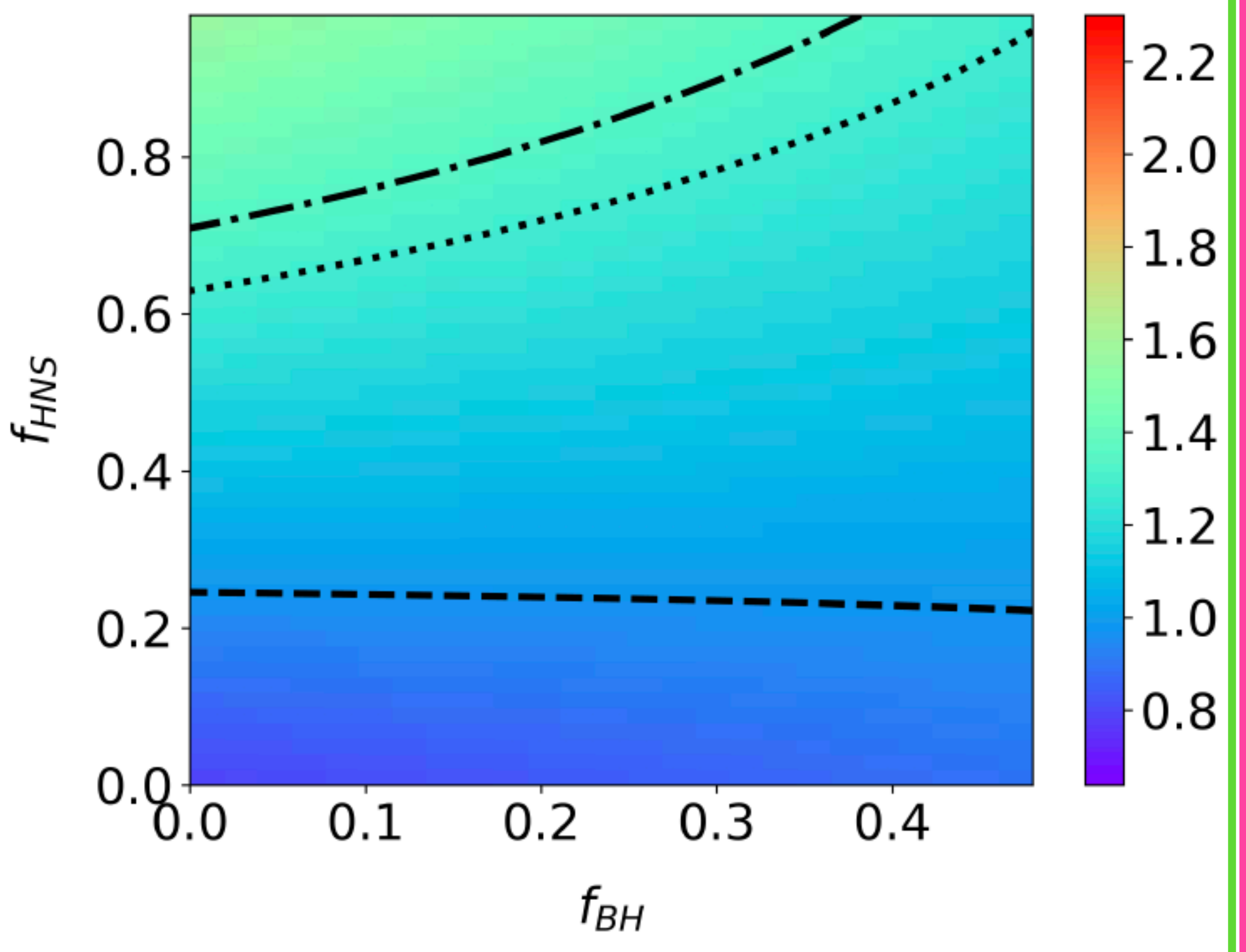
(1b) LS220 EOS, $13.3 < E_\nu < 31.3\,\mathrm{MeV}$



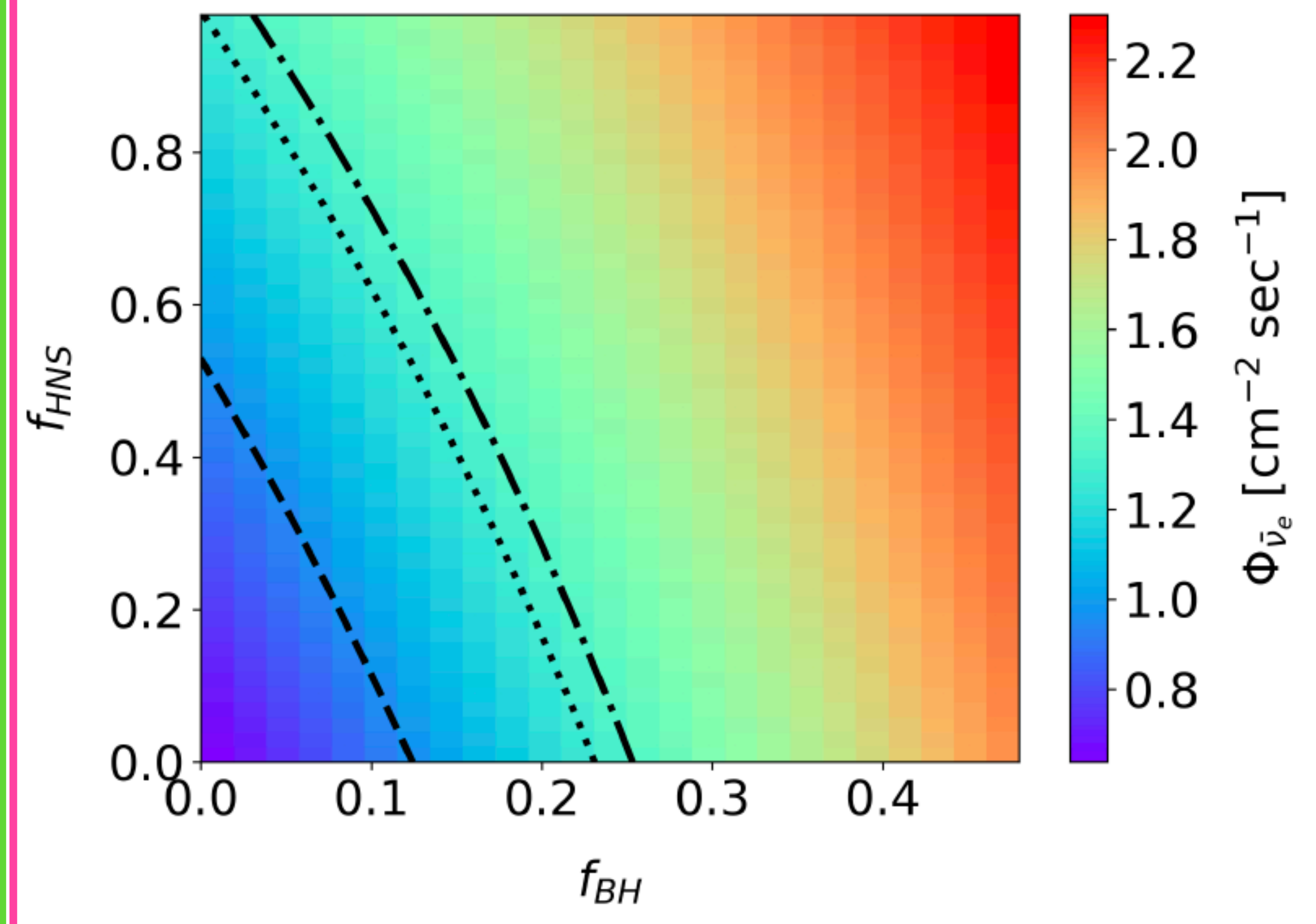
(1c) Shen EOS, $13.3 < E_\nu < 31.3\,\mathrm{MeV}$



(2a) Togashi EOS, $17.3 < E_\nu < 31.3\,\mathrm{MeV}$



(2b) LS220 EOS, $17.3 < E_\nu < 31.3\,\mathrm{MeV}$



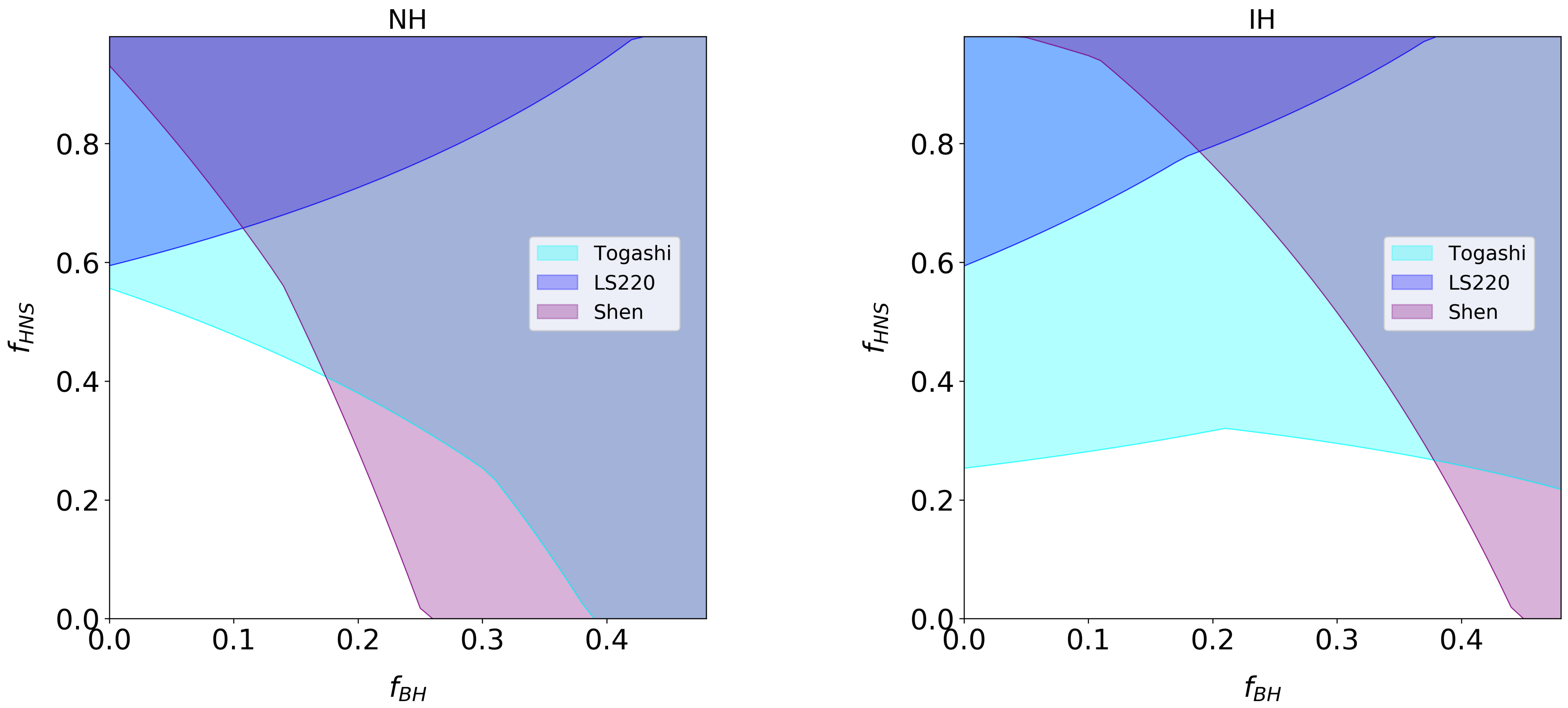
(2c) Shen EOS, $17.3 < E_\nu < 31.3\,\mathrm{MeV}$

Togashi

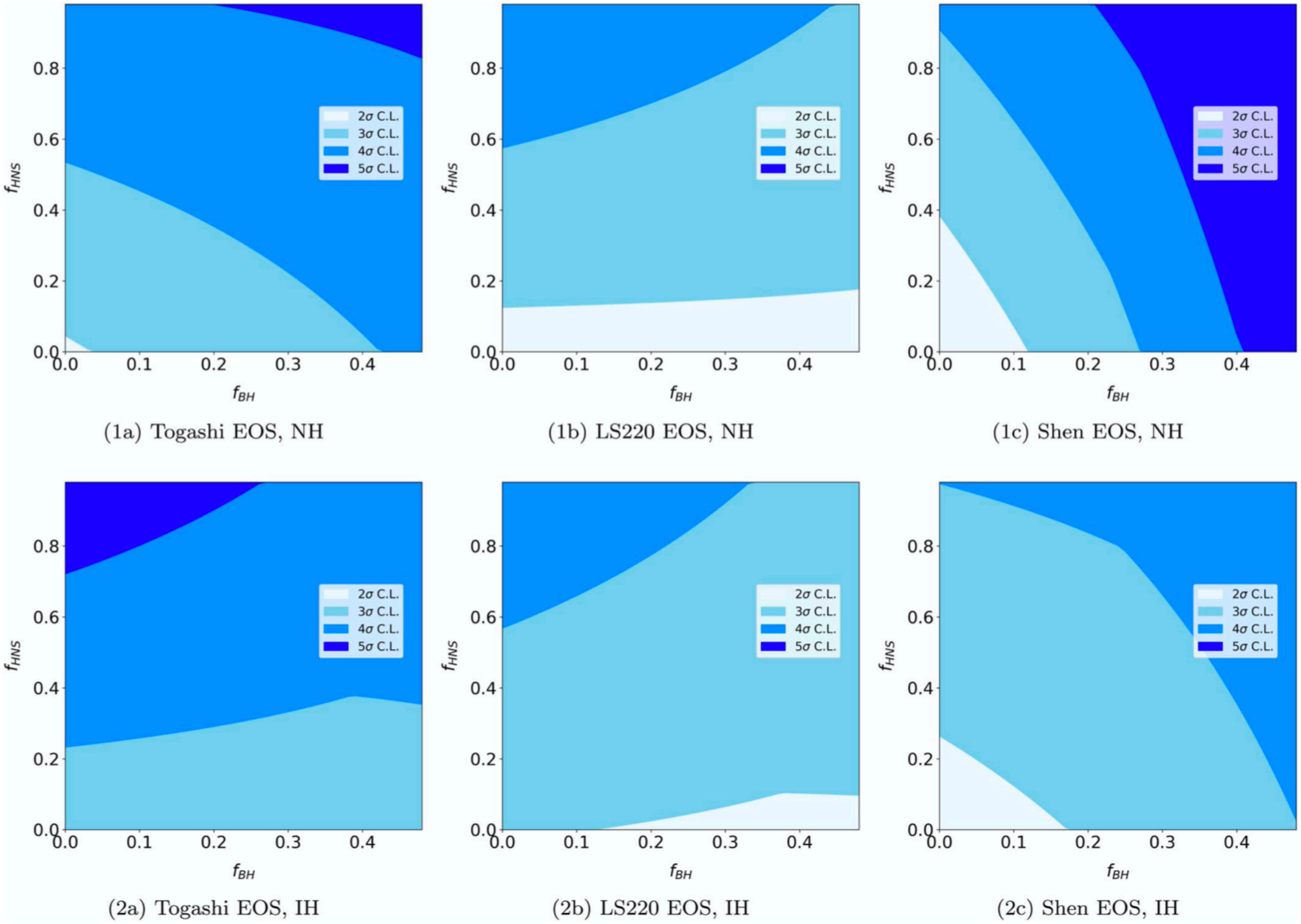
LS220

Shen

Nuclear EOS Dependence



Hyper-K Sensitivity



(1a) Togashi EOS, NH

(1b) LS220 EOS, NH

(1c) Shen EOS, NH

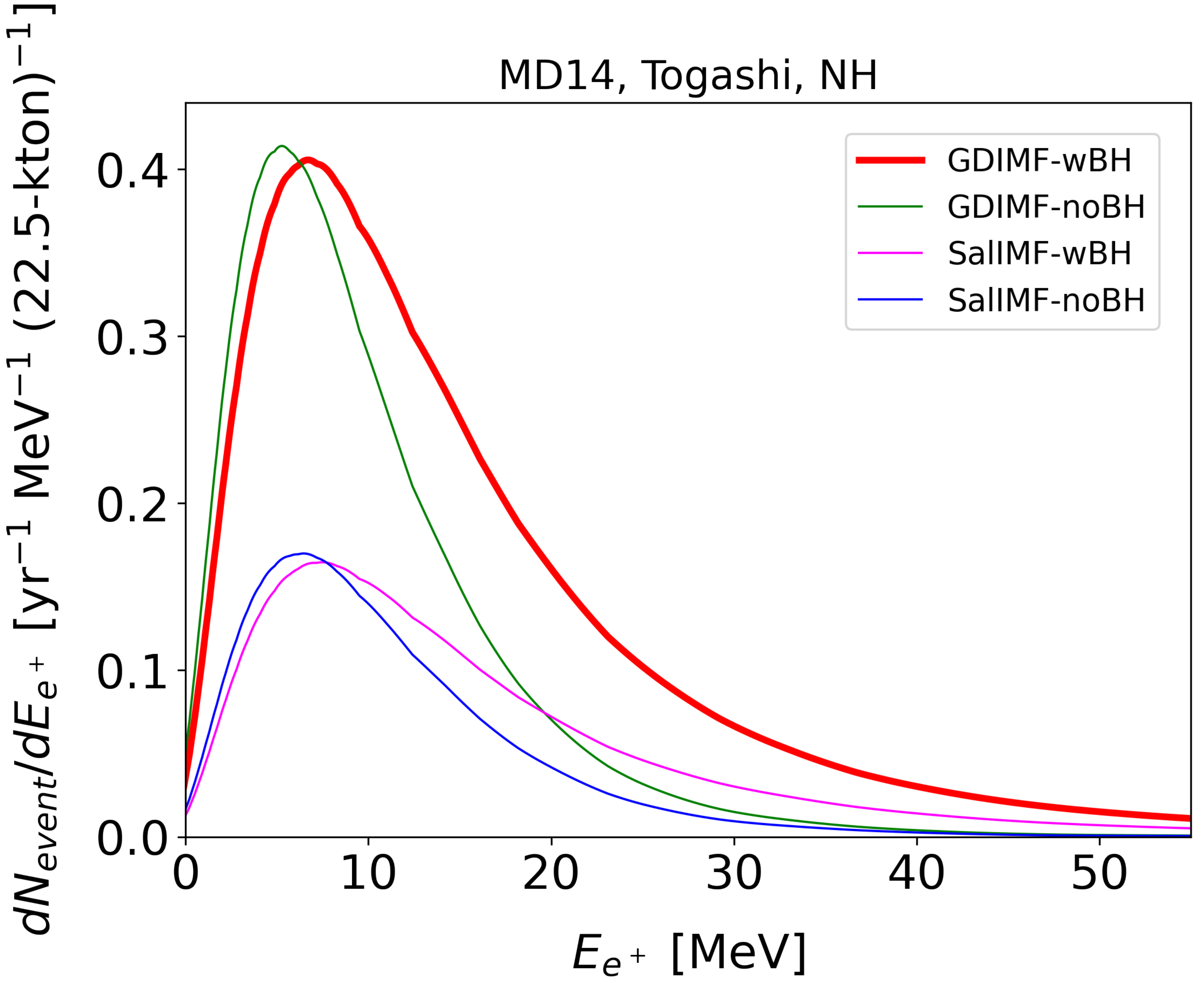
(2a) Togashi EOS, IH

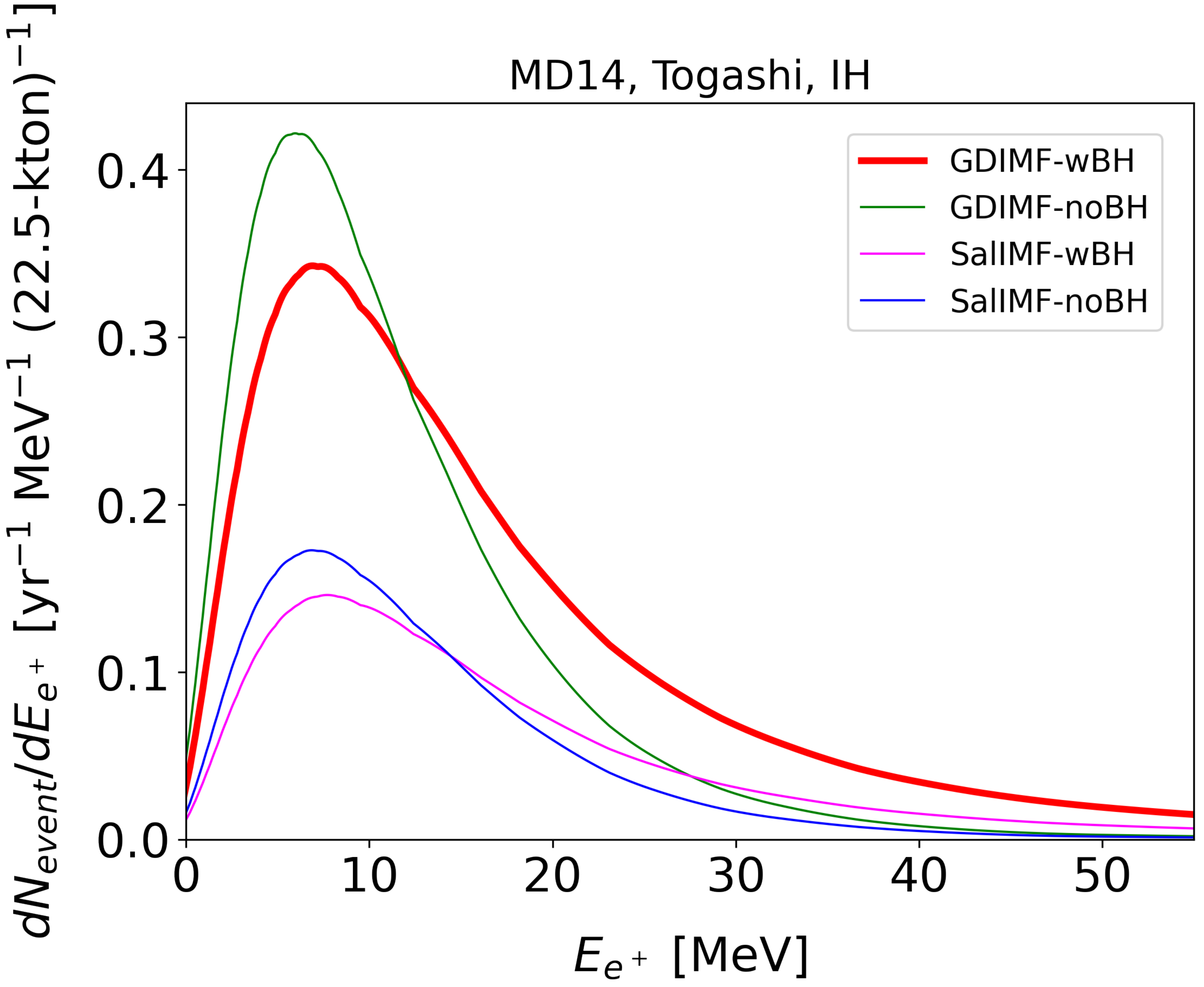
(2b) LS220 EOS, IH

(2c) Shen EOS, IH

Event Rate

- Event rate spectrum at a water volume is calculated with IBD cross section.
- SK-Gd w/ 70% ntag efficiency over 10yr = 15~18 signals
- Hyper-K w/ Super-K ntag efficiency over 10yr = 50~60 signals





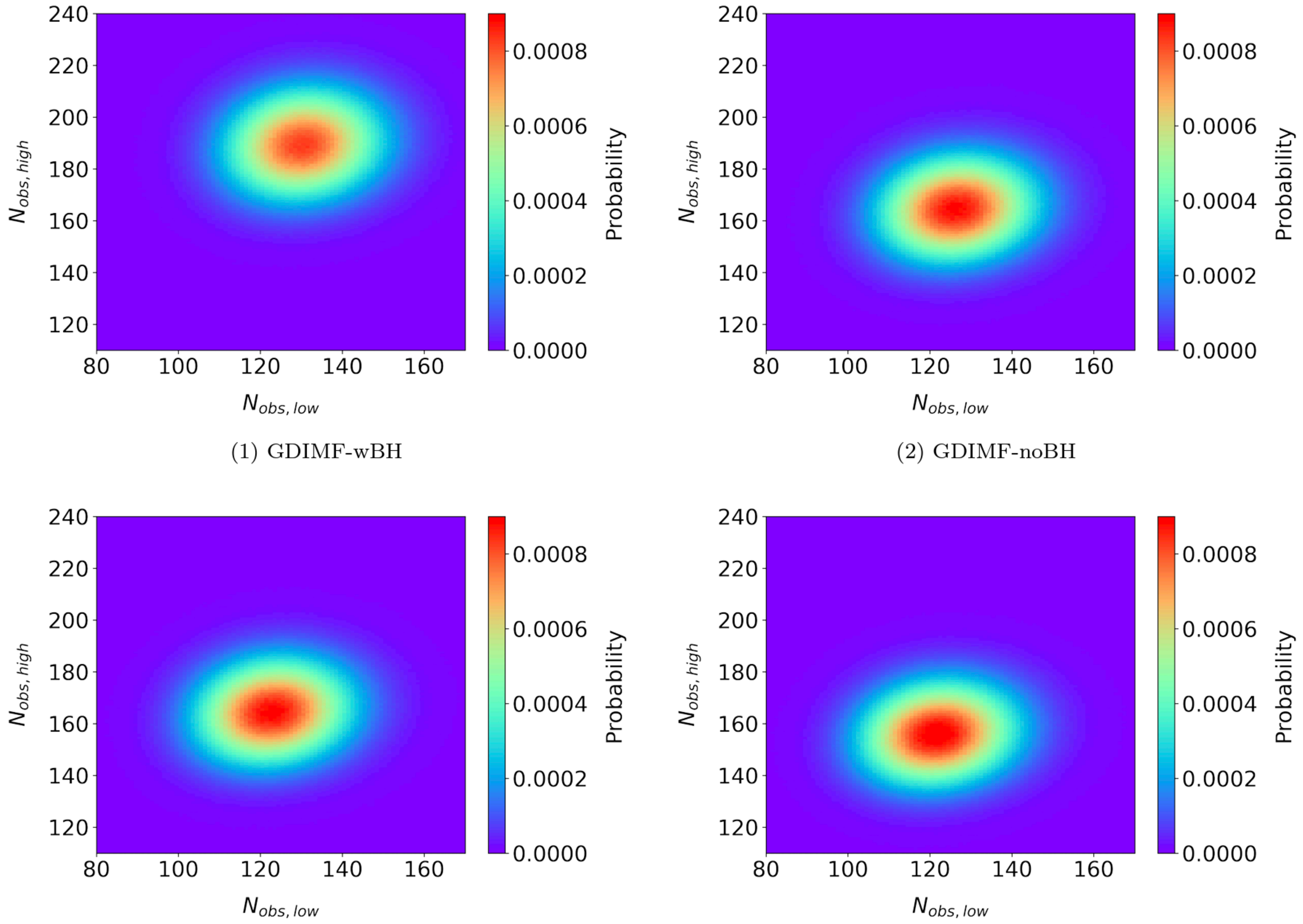
Sensitivity Estimation

Bayes' theorem:

$$\underbrace{\boxed{P(\mathrm{model}|\mathrm{data})}}_{\text{Posterior}} = \frac{\overbrace{\boxed{P(\mathrm{data}|\mathrm{model})}}^{\text{Likelihood (frequentist)}} \times \overbrace{\boxed{P(\mathrm{model})}}^{\text{Prior}}}{\underbrace{\boxed{\sum_{\mathrm{model}} P(\mathrm{data}|\mathrm{model}) \times P(\mathrm{model})}}_{\text{Normalization}}}$$

- Prior: *P*(model) = 1/N for testing N models.
- Likelihood: prepared based on signal+background expectations for each model.
- Utilize two energy ranges (13.3–17.3 MeV & 17.3–31.3 MeV).
- Use real data for SK-IV, and nominal expectations for SK-Gd and Hyper-K.

Likelihood



(1) GDIMF-wBH

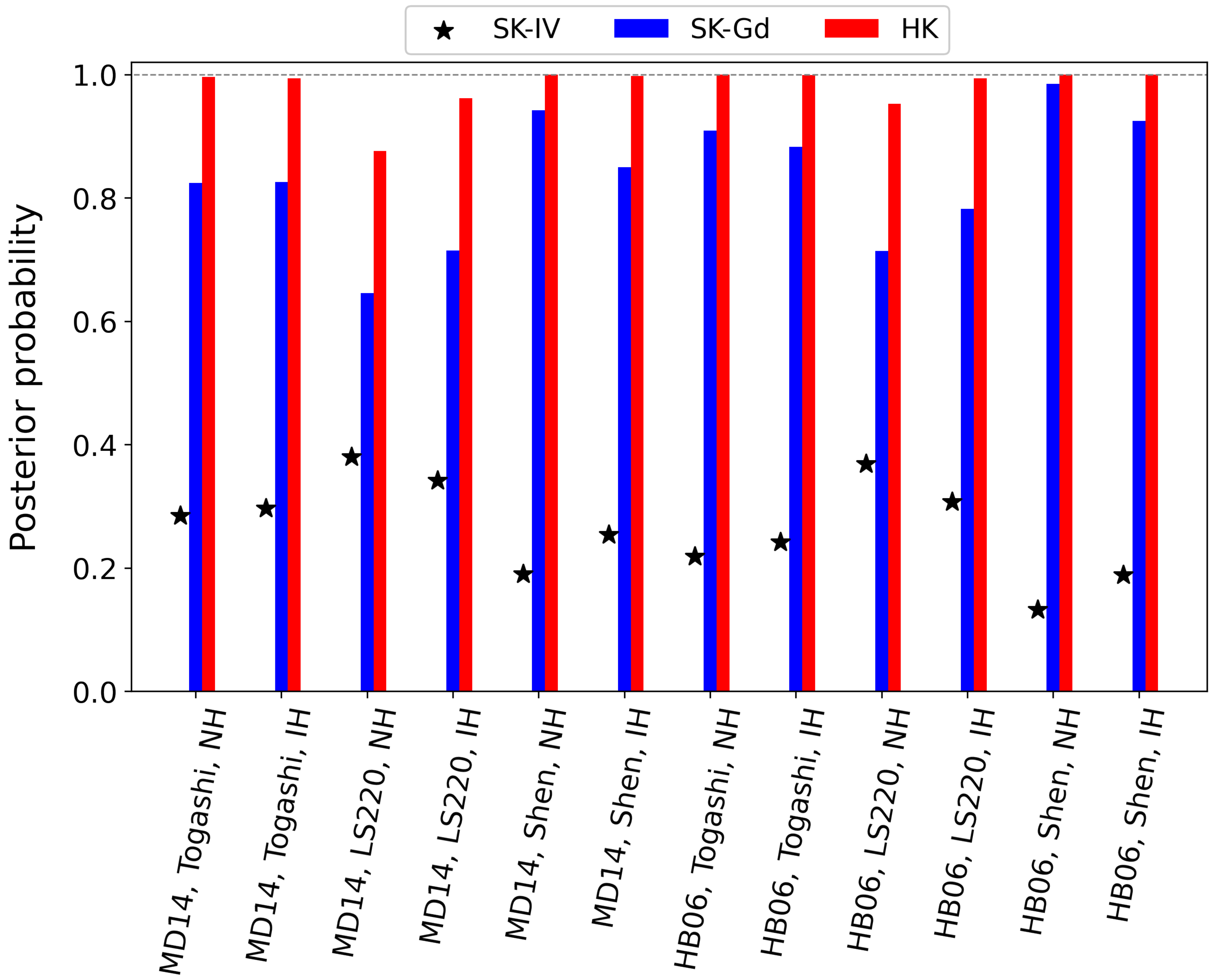
(2) GDIMF-noBH

(3) SalIMF-wBH

(4) SalIMF-noBH

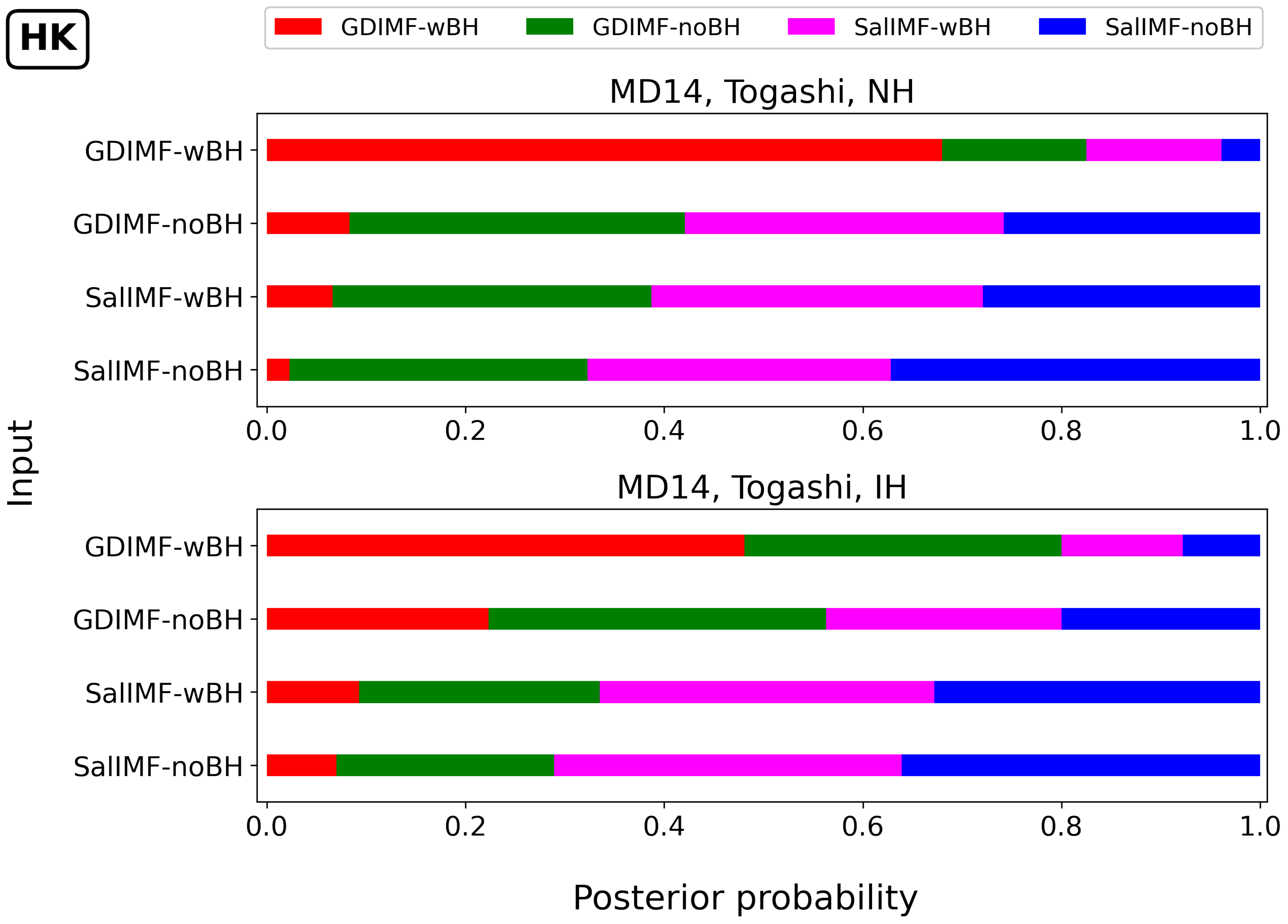
Signal Significance

- Our reference model is tested against background only at different detectors based on Bayes' theorem.
- Background model used for likelihood is based on extrapolation from Super-K analysis.
- In most cases, our signal models can be detected well over background.

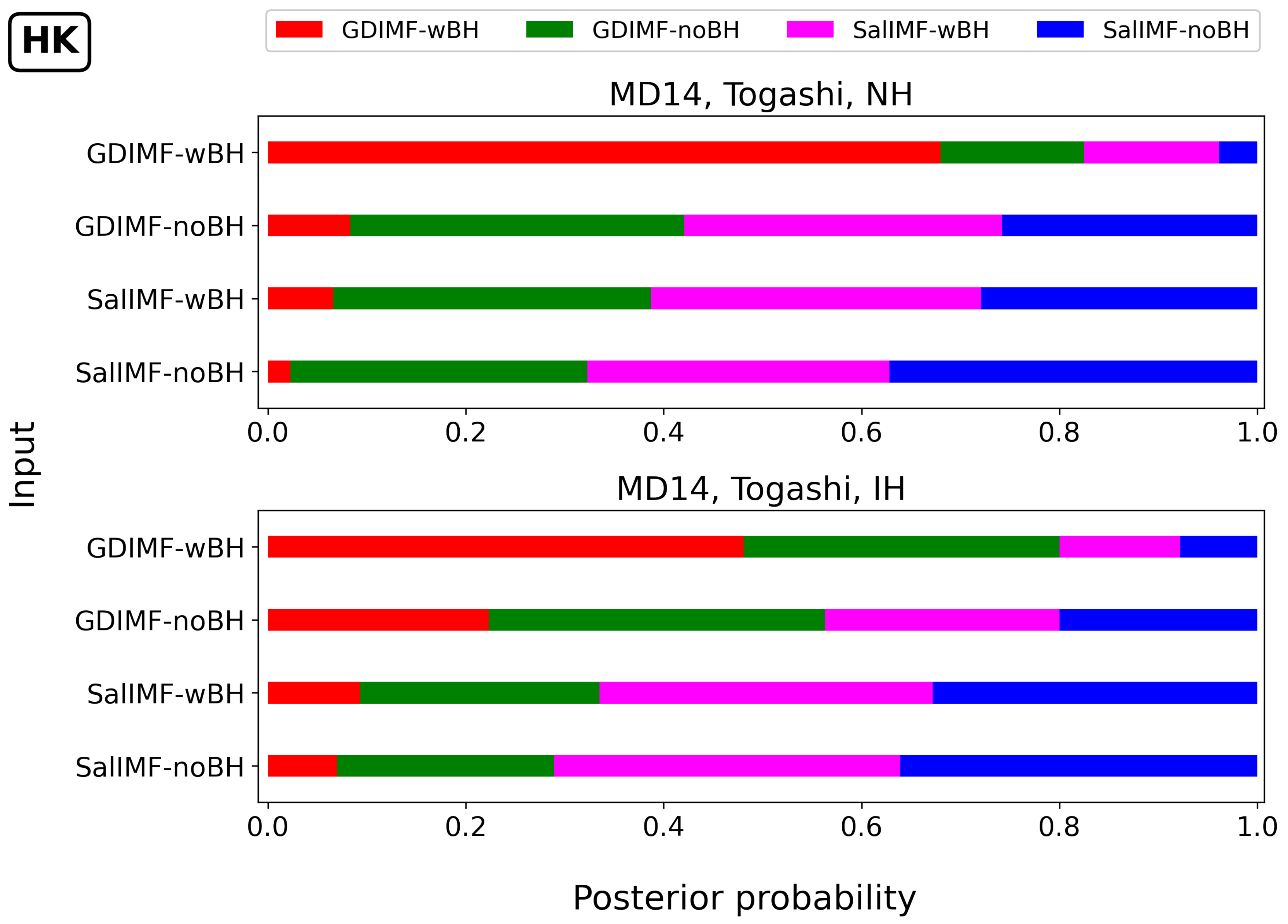


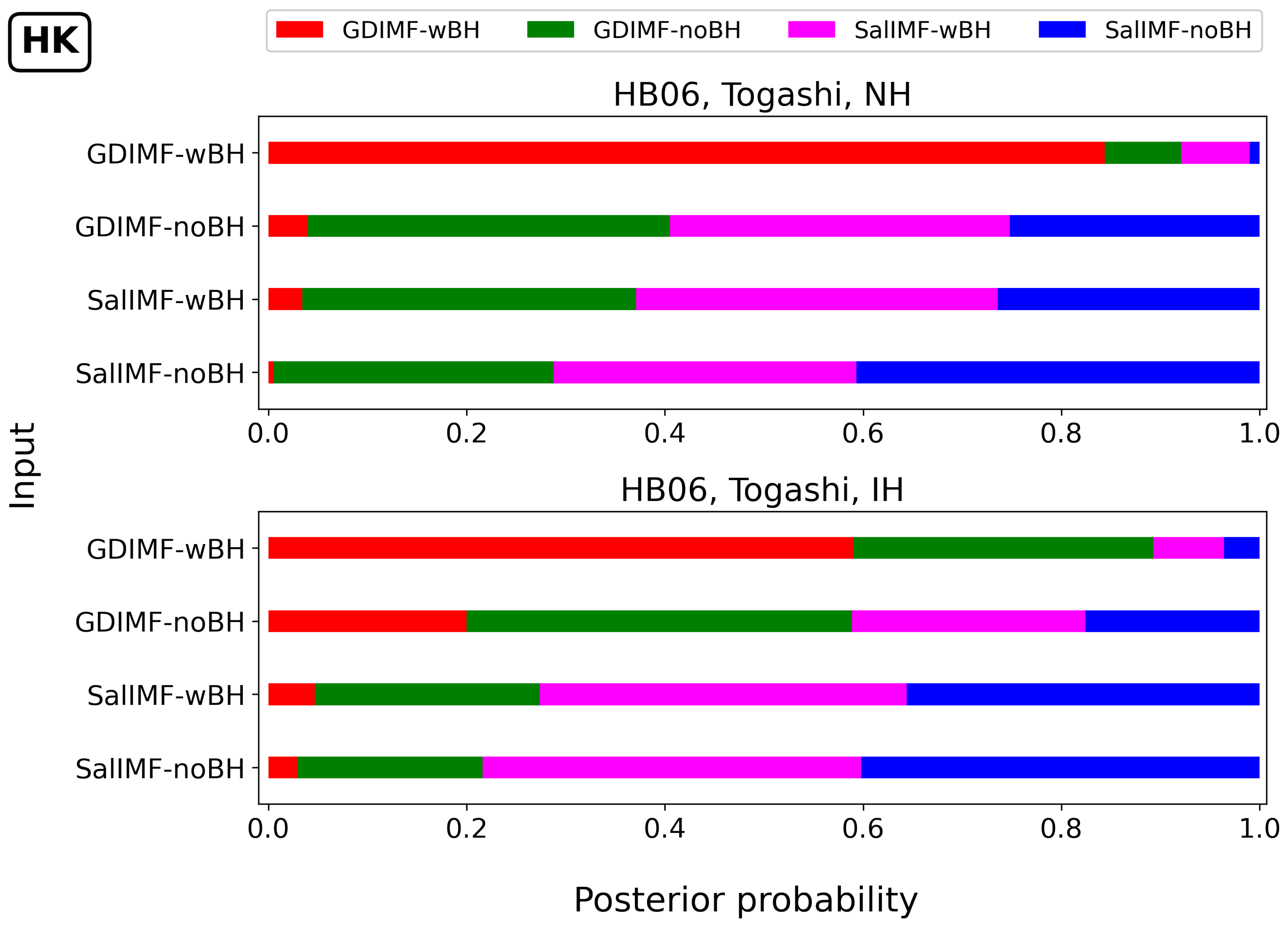
Model Discrimination

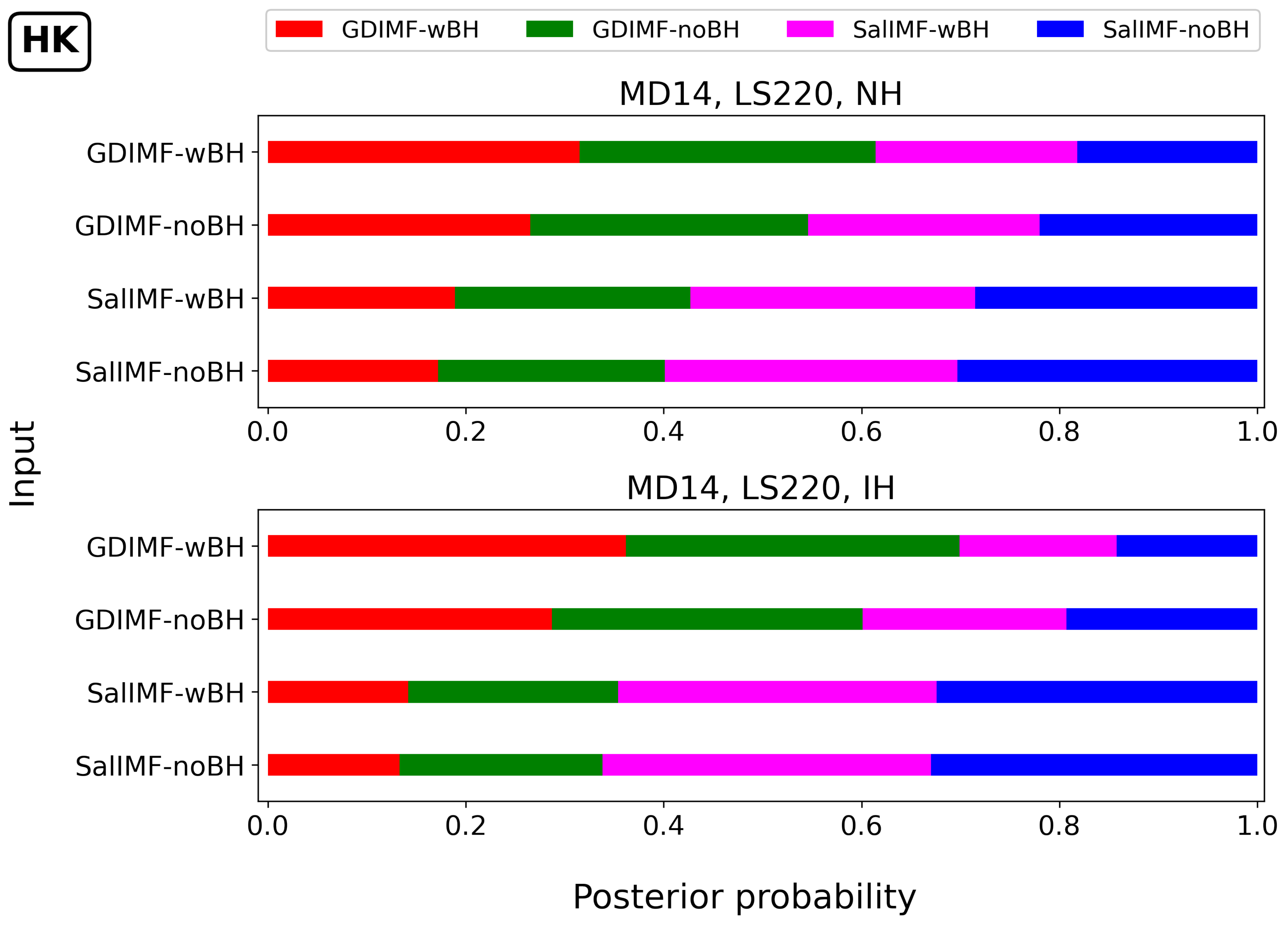
- Our reference model is tested against alternative models with different assumptions on IMF and BH.
- In NH case, the reference model is well discriminated from others.
- In IH case, only IMF assumption can be tested well.
- The results differ for other choices of SFR and nuclear EOS (all results are discussed in the paper).

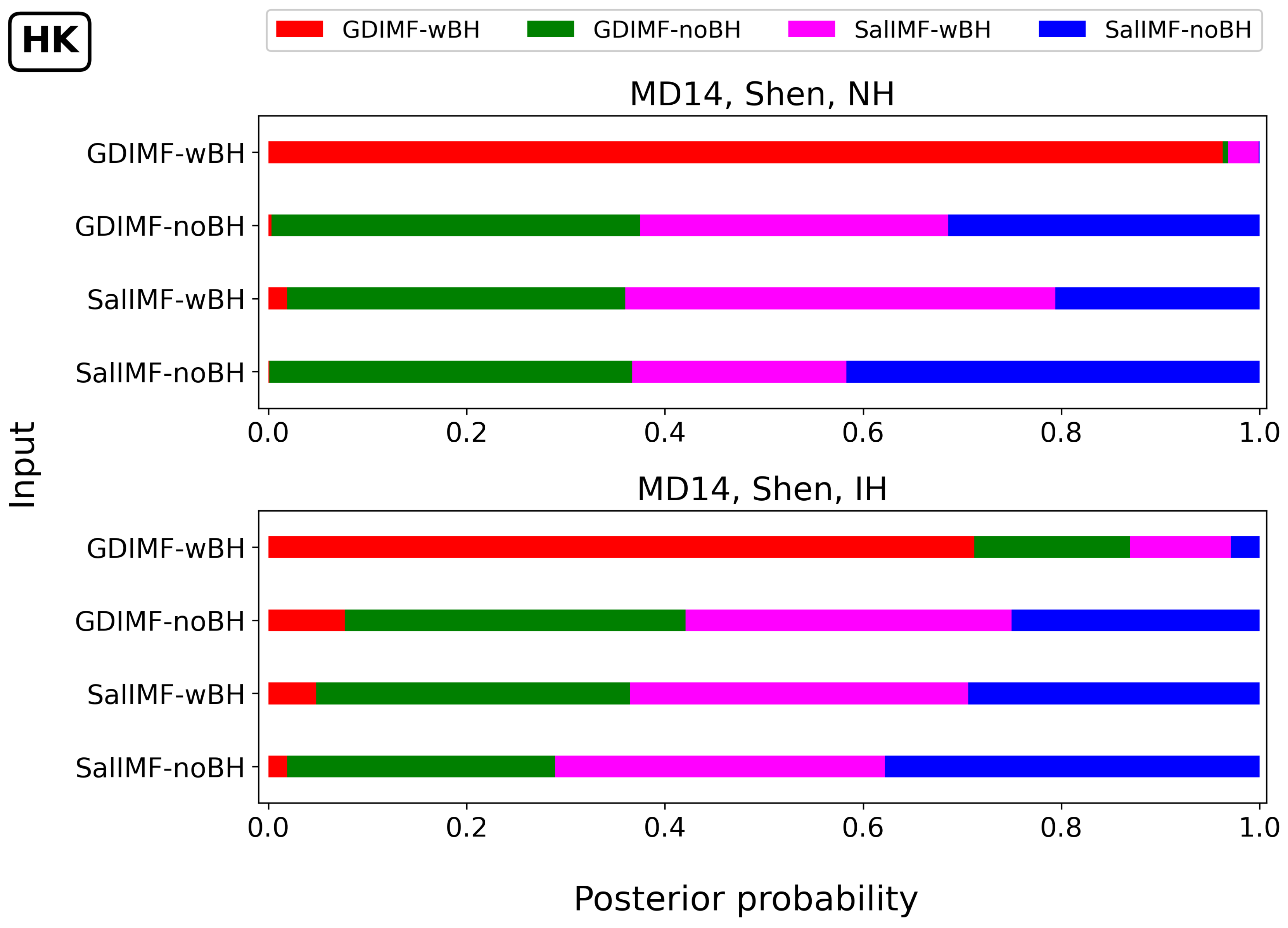


EOS & SFR Dependences





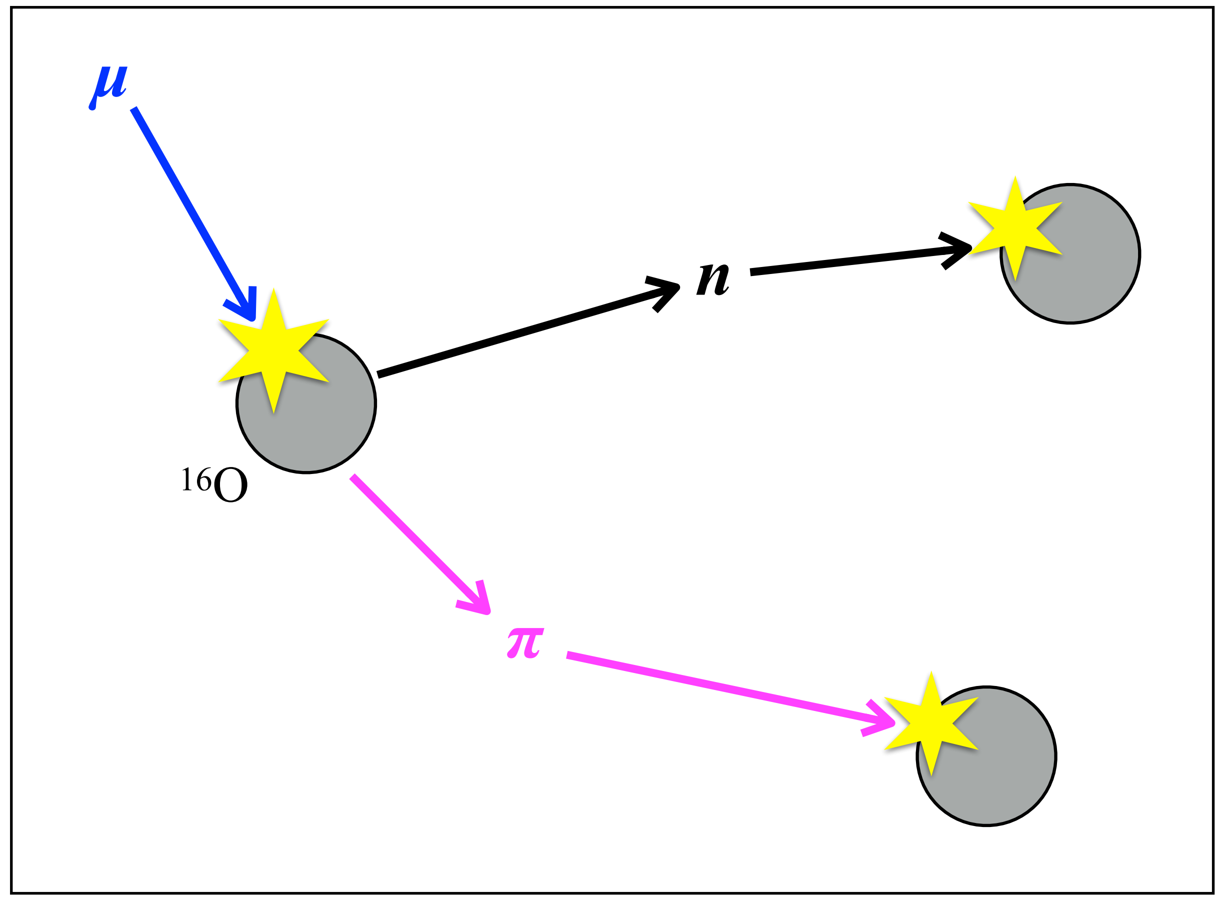




Muon Spallation

Muon spallation

- Decay without neutron
- Decay with neutron (^{9}Li, etc)



Energetic atmospheric μ on oxygen in Super-K

↓

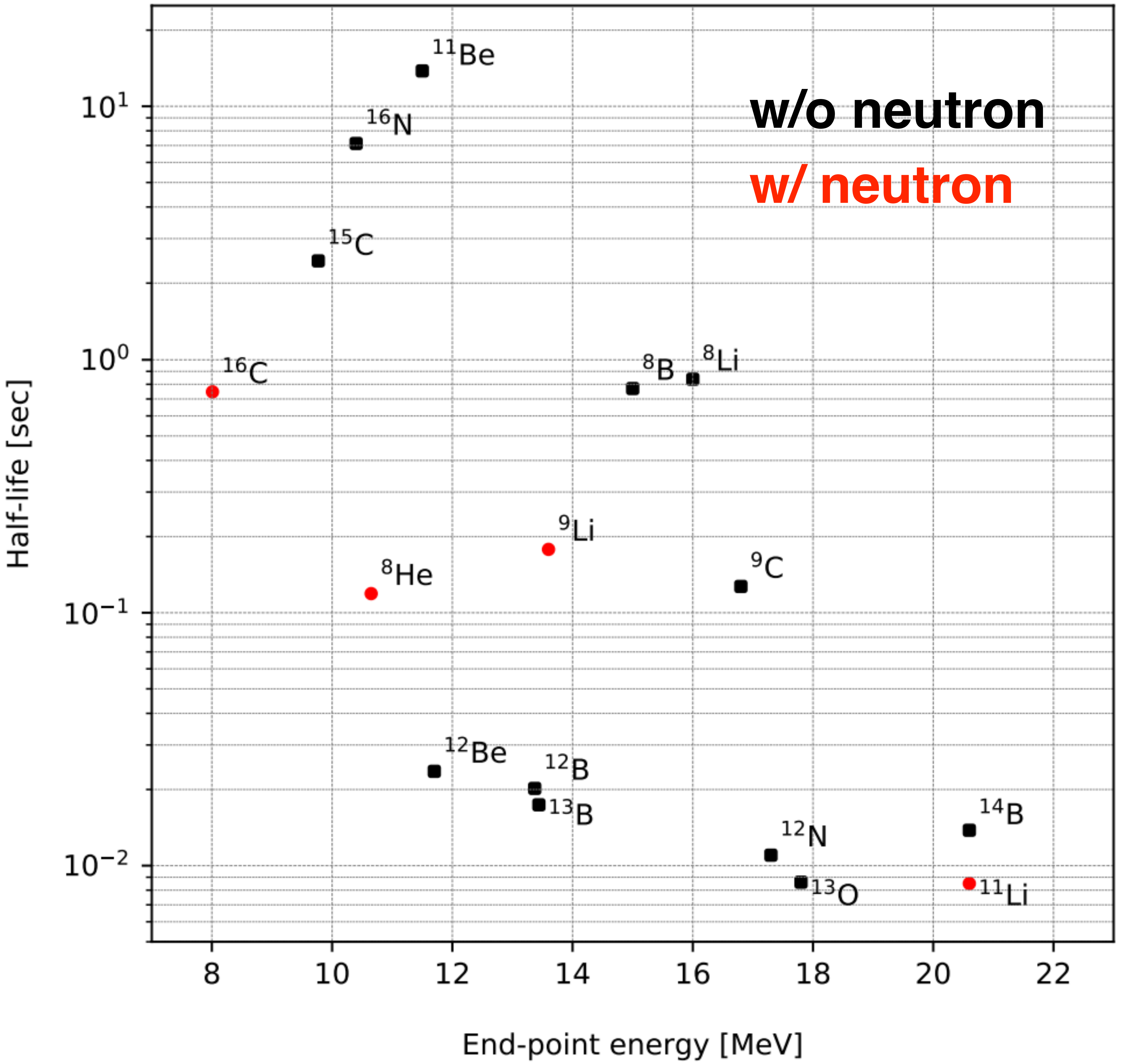
Hadronic particles

↓

Radioactive isotopes

↓

β/γ decay (delayed by msec~10 sec)



Muons for Spallation

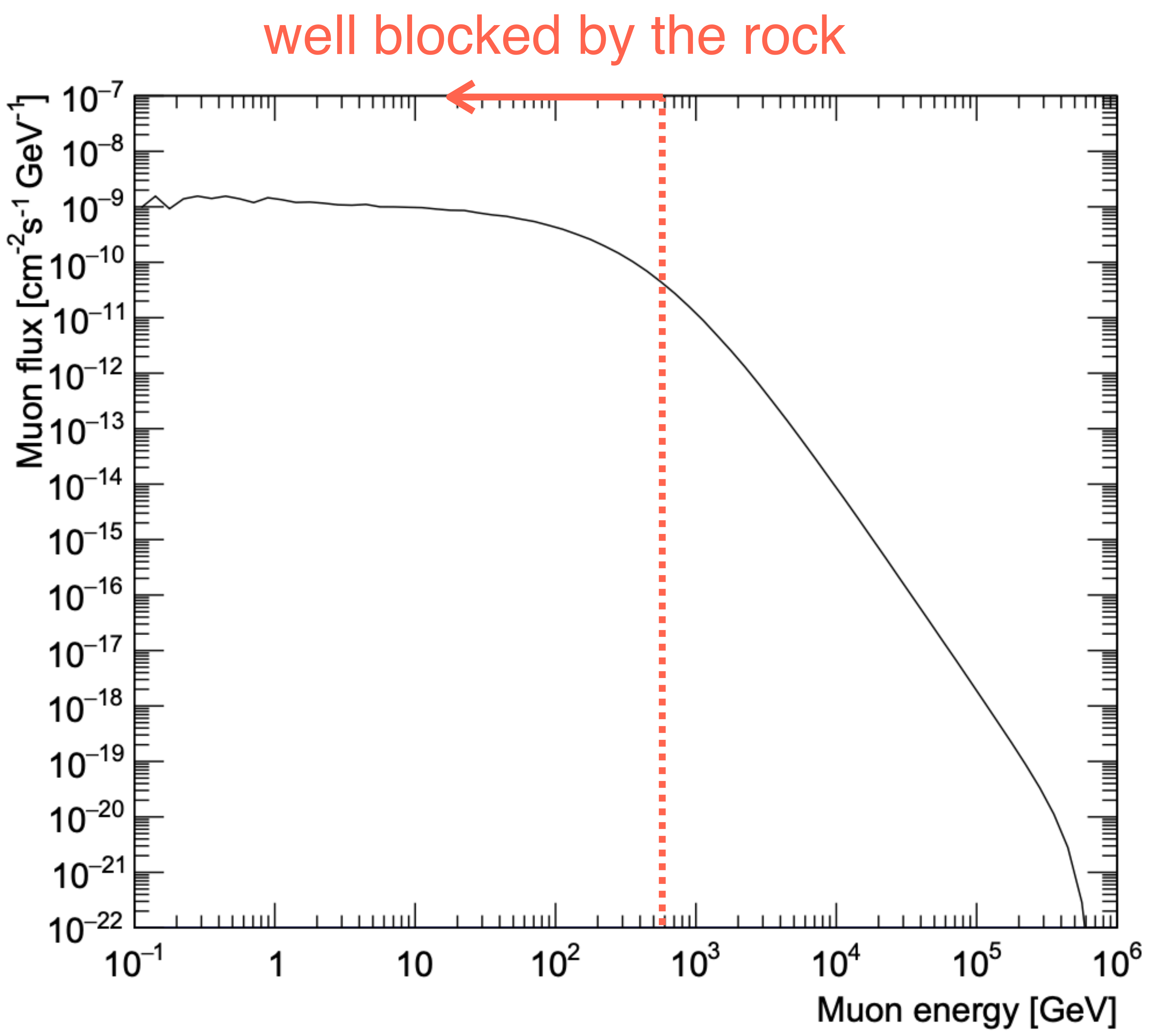
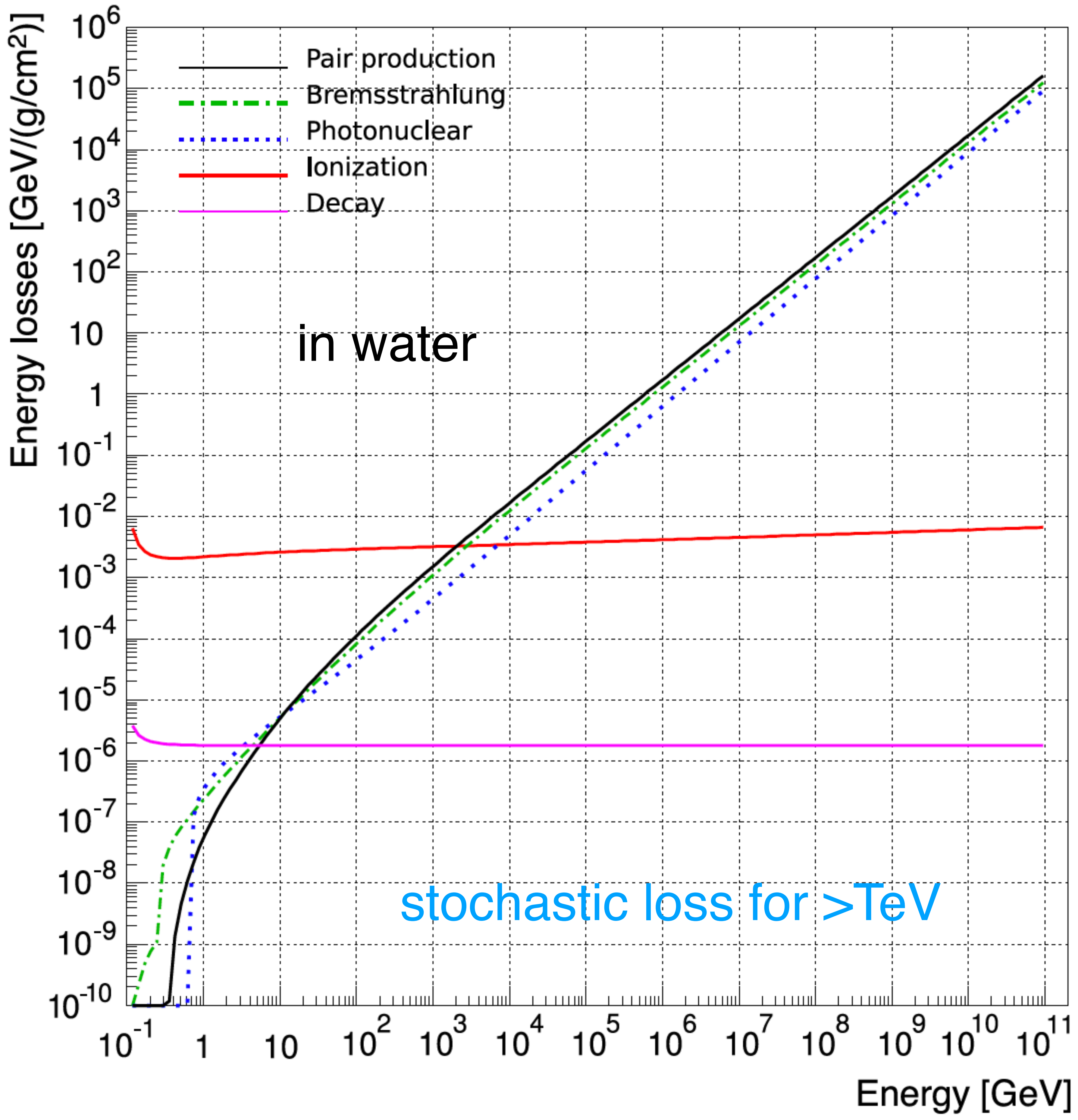


FIG. 2. Muon energy spectrum at the location of SK detector in the mine inside Mt. Ikenoyama.



Spallation by FLUKA

S. W. Li and J. F. Beacom, Phys. Rev. C 89, 045801 (2014)
S. W. Li and J. F. Beacom, Phys. Rev. D 91, 105005 (2015)

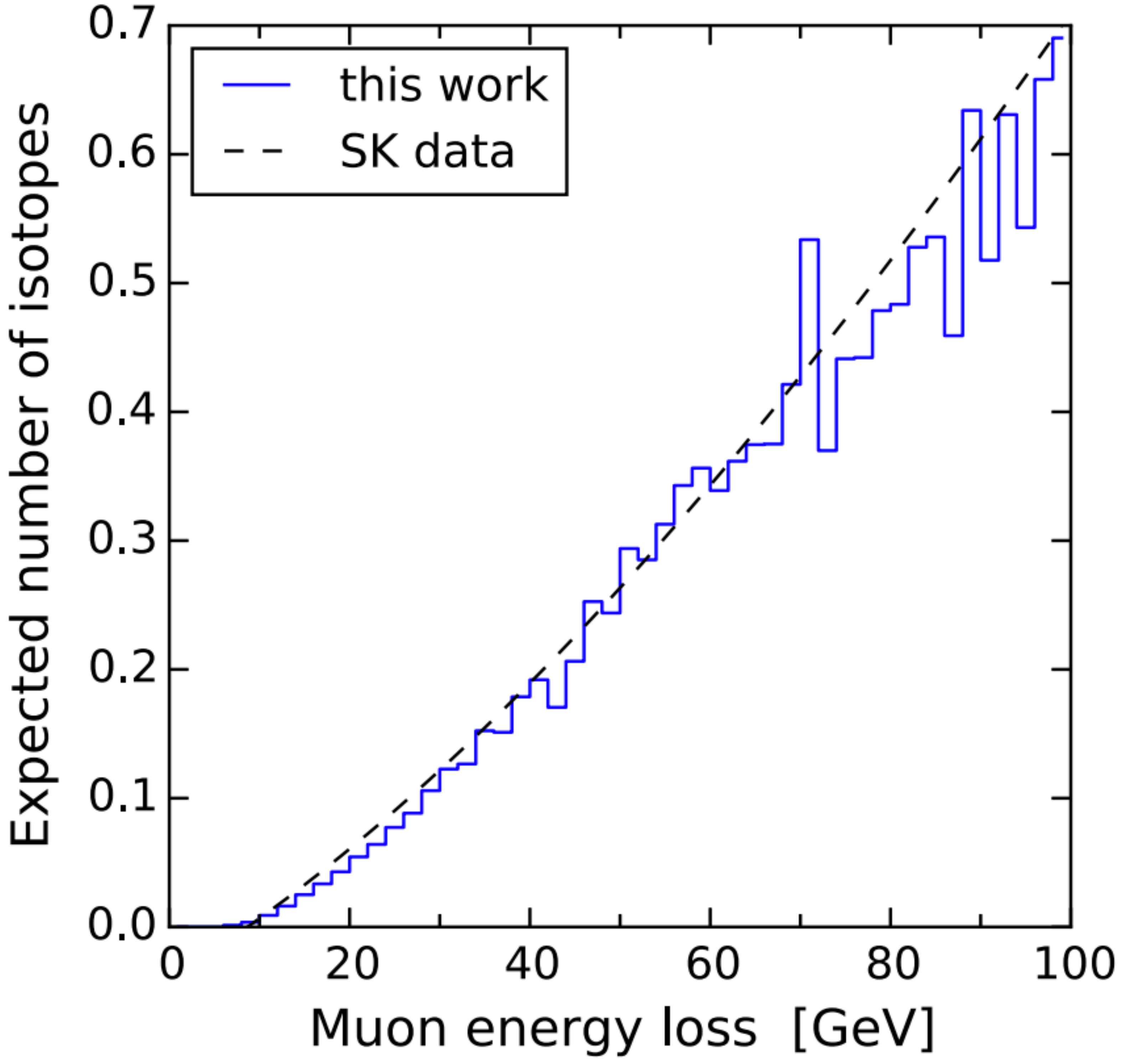


FIG. 8 (color online). The expected number of background isotopes as a function of the total muon energy loss. The solid line is our calculation assuming vertical through going muons that travel 32.2 m in the FV, and the dashed line is the (corrected to match assumptions) Super-K measurement.

Isotope	Half-life (s)	Decay mode	Yield (total) ($\times 10^{-7}\mu^{-1}g^{-1}cm^2$)	Yield ($E > 3.5$ MeV) ($\times 10^{-7}\mu^{-1}g^{-1}cm^2$)	Primary process
n			2030		
^{18}N	0.624	β^-	0.02	0.01	^{18}O(n,p)
^{17}N	4.173	$\boxed{\beta^- n}$	0.59	0.02	^{18}O($n,n+p$)
^{16}N	7.13	$\beta^-\gamma$ (66%), β^- (28%)	18	18	(n,p)
^{16}C	0.747	$\boxed{\beta^- n}$	0.02	0.003	($\pi^-,n+p$)
^{15}C	2.449	$\beta^-\gamma$ (63%), β^- (37%)	0.82	0.28	($n,2p$)
^{14}B	0.0138	$\beta^-\gamma$	0.02	0.02	($n,3p$)
^{13}O	0.0086	β^+	0.26	0.24	($\mu^-,p+2n+\mu^-+\pi^-$)
^{13}B	0.0174	β^-	1.9	1.6	($\pi^-,2p+n$)
^{12}N	0.0110	β^+	1.3	1.1	($\pi^+,2p+2n$)
^{12}B	0.0202	β^-	12	9.8	($n,\alpha+p$)
^{12}Be	0.0236	β^-	0.10	0.08	($\pi^-,\alpha+p+n$)
^{11}Be	13.8	β^- (55%), $\beta^-\gamma$ (31%)	0.81	0.54	($n,\alpha+2p$)
^{11}Li	0.0085	$\boxed{\beta^- n}$	0.01	0.01	($\pi^+,5p+\pi^++\pi^0$)
^{9}C	0.127	β^+	0.89	0.69	($n,\alpha+4n$)
^{9}Li	0.178	$\boxed{\beta^- n}$(51%), β^- (49%)	1.9	1.5	($\pi^-,\alpha+2p+n$)
^{8}B	0.77	β^+	5.8	5.0	($\pi^+,\alpha+2p+2n$)
^{8}Li	0.838	β^-	13	11	($\pi^-,\alpha+{}^2$H$+p+n$)
^{8}He	0.119	$\beta^-\gamma$ (84%), $\boxed{\beta^- n}$(16%)	0.23	0.16	($\pi^-,{}^3$H$+4p+n$)
^{15}O			351		(γ,n)
^{15}N			773		(γ,p)
^{14}O			13		($n,3n$)
^{14}N			295		($\gamma,n+p$)
^{14}C			64		($n,n+2p$)
^{13}N			19		($\gamma,{}^3$H)
^{13}C			225		($n,{}^2$H$+p+n$)
^{12}C			792		(γ,α)
^{11}C			105		($n,\alpha+2n$)
^{11}B			174		($n,\alpha+p+n$)
^{10}C			7.6		($n,\alpha+3n$)
^{10}B			77		($n,\alpha+p+2n$)
^{10}Be			24		($n,\alpha+2p+n$)
^{9}Be			38		($n,2\alpha$)
sum			3015	50	

^{18}O is very little (~0.2%)

small amount >3.5 MeV

very short life-time

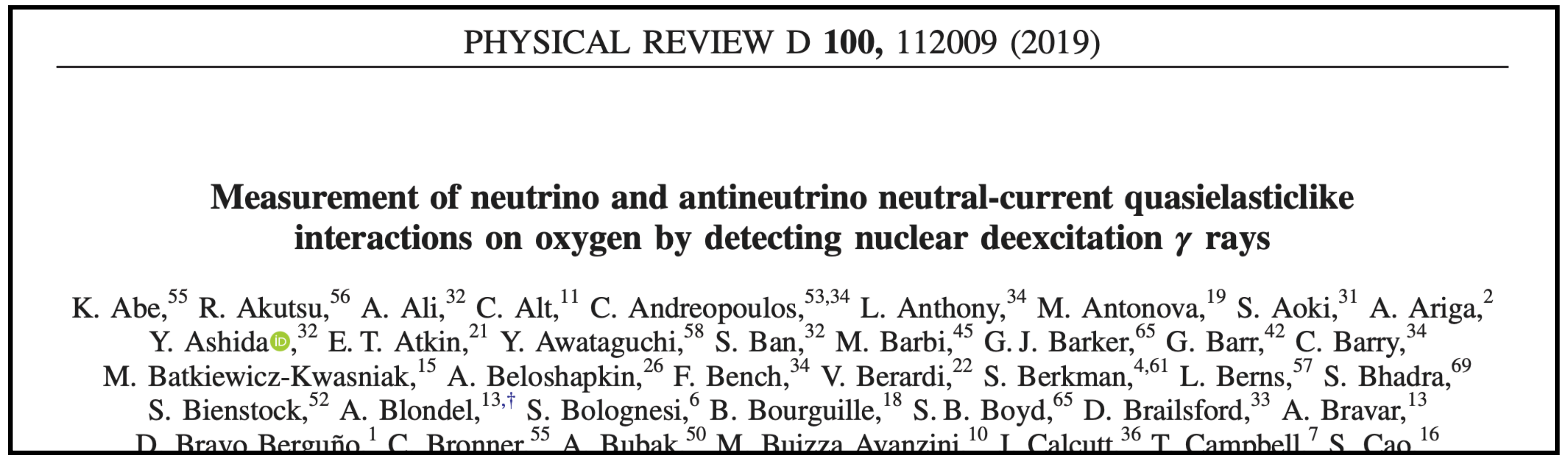
low energy (end point ~8 MeV)

Not direct backgrounds in SK:

- stable
- long half-life
- invisible decay
- low energy

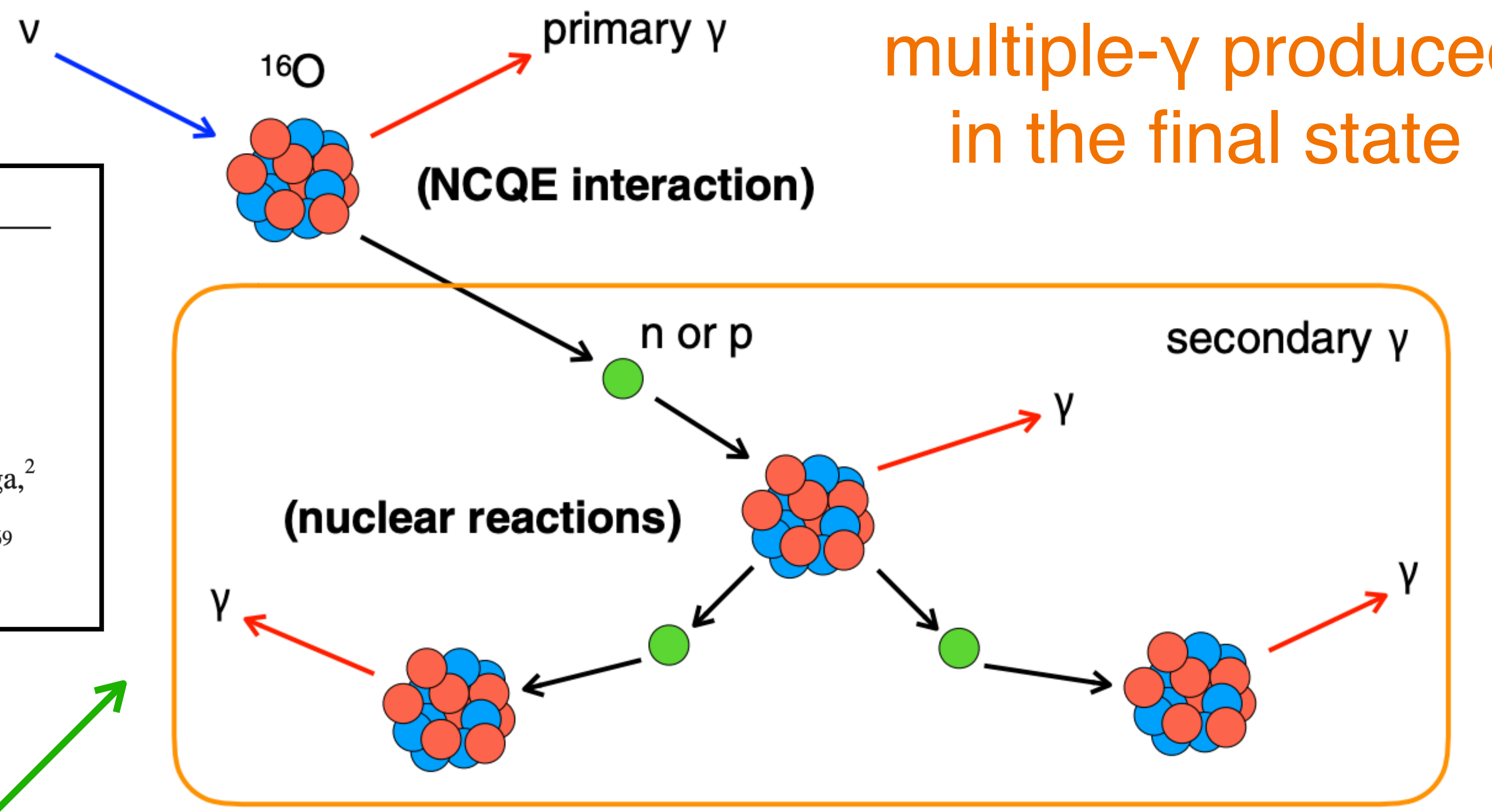
Atmospheric Neutrinos

★ My own analysis in T2K


PHYSICAL REVIEW D **100,** 112009 (2019)

Measurement of neutrino and antineutrino neutral-current quasielasticlike interactions on oxygen by detecting nuclear deexcitation γ rays

K. Abe,[55] R. Akutsu,[56] A. Ali,[32] C. Alt,[11] C. Andreopoulos,[53,34] L. Anthony,[34] M. Antonova,[19] S. Aoki,[31] A. Ariga,[2] Y. Ashida,[32] E. T. Atkin,[21] Y. Awataguchi,[58] S. Ban,[32] M. Barbi,[45] G. J. Barker,[65] G. Barr,[42] C. Barry,[34] M. Batkiewicz-Kwasniak,[15] A. Beloshapkin,[26] F. Bench,[34] V. Berardi,[22] S. Berkman,[4,61] L. Berns,[57] S. Bhadra,[69] S. Bienstock,[52] A. Blondel,[13,†] S. Bolognesi,[6] B. Bourguille,[18] S. B. Boyd,[65] D. Brailsford,[33] A. Bravar,[13] D. Bravo Berguño,[1] C. Bronner,[55] A. Bubak,[50] M. Buizza Avanzini,[10] J. Calcutt,[36] T. Campbell,[7] S. Cao,[16]

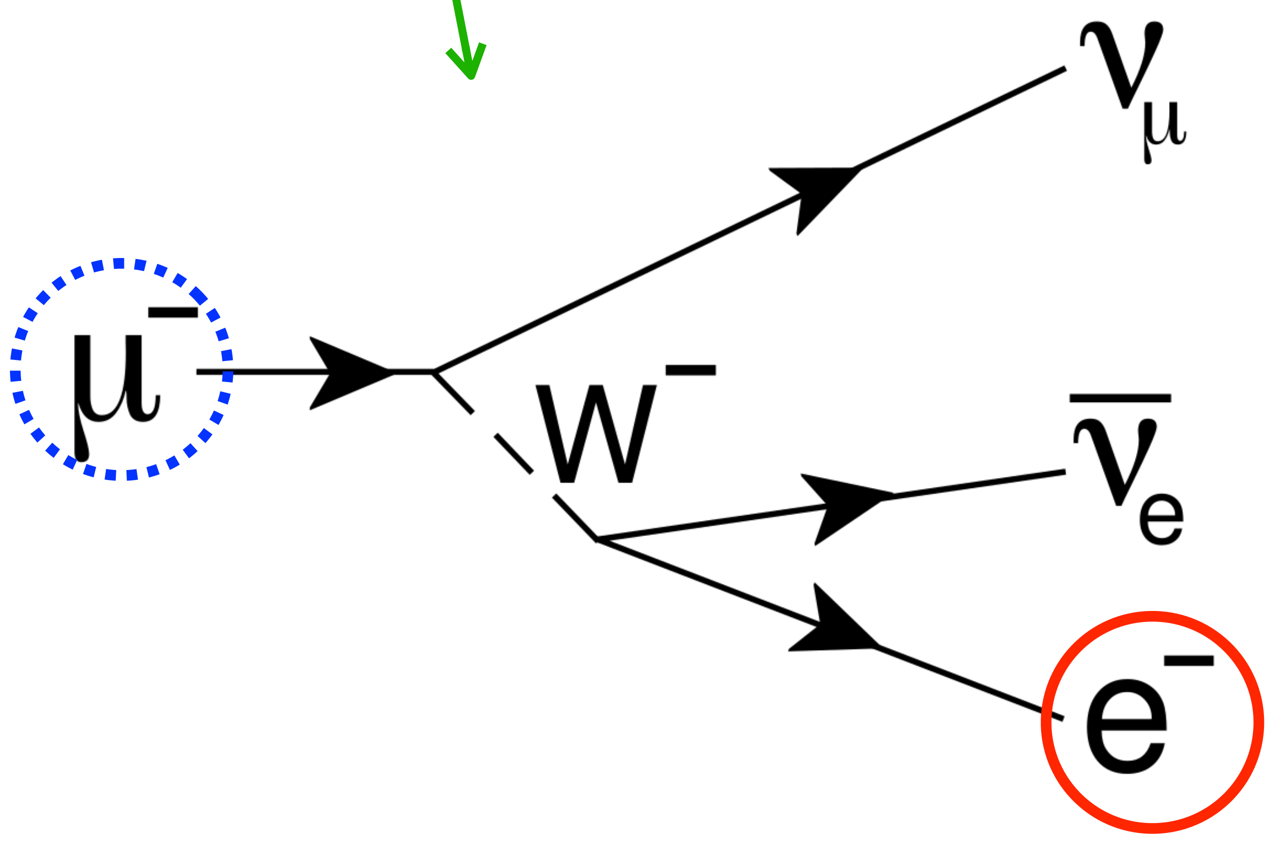


multiple-γ produced in the final state

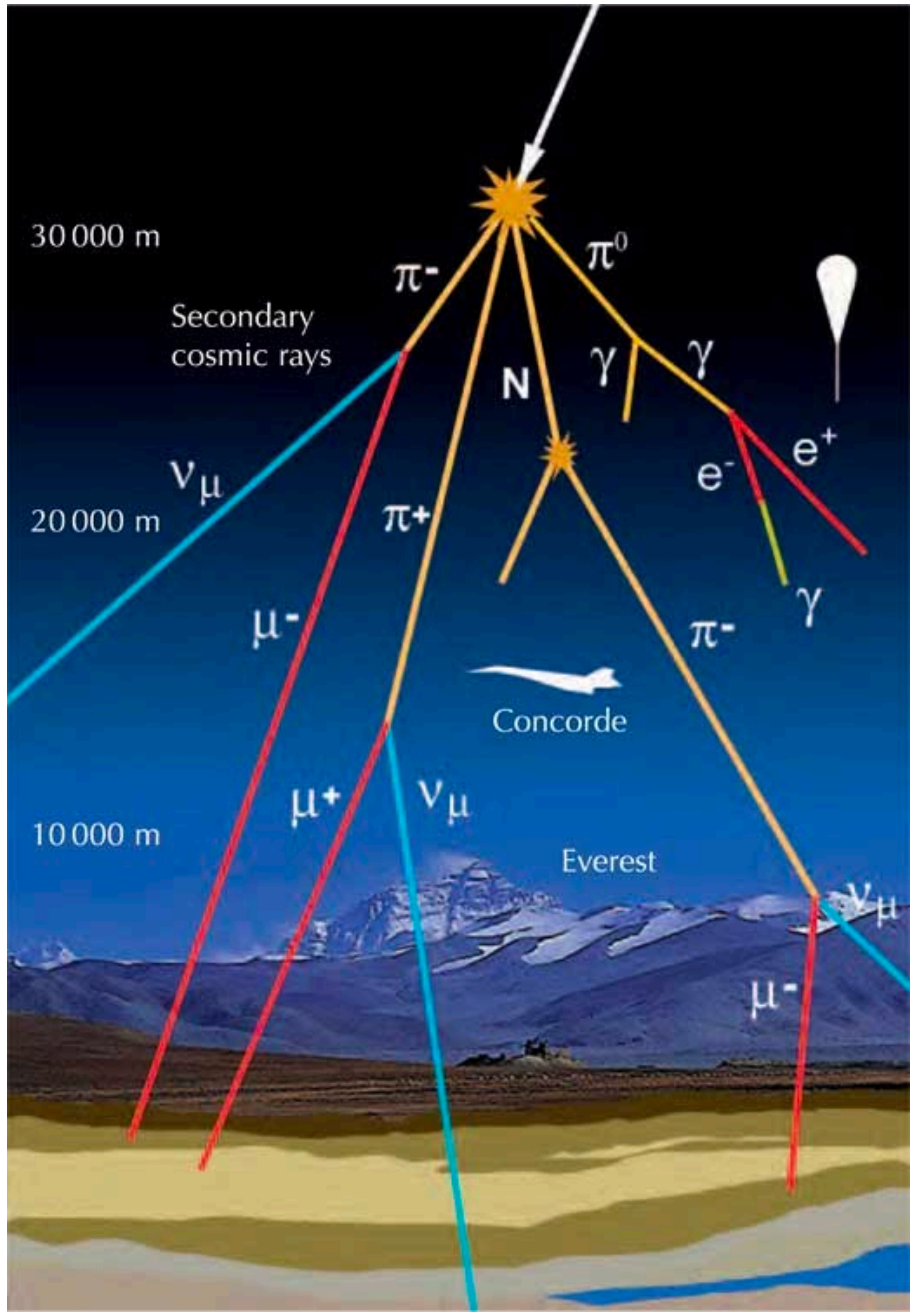
Atmospheric neutrinos

- Neutral-current quasielastic interactions (NCQE)
- $\nu_e/\bar{\nu}_e$ charged-current (CC) interactions
- Muon/pion-producing interactions (CCQE, CC1π, NC1π, etc)

invisible (<120 MeV/c)



visible (decay-e)



Background: Experimental Classification

Classification by physical source

Muon spallation
- Decay without neutron
- Decay with neutron (^{9}Li, etc)

Atmospheric neutrinos
- Neutral-current quasielastic interactions (NCQE)
- $\nu_e/\bar{\nu}_e$ charged-current (CC) interactions
- Muon/pion-producing interactions (CCQE, CC1π, NC1π, etc)

Solar neutrinos (electron scattering)

Reactor neutrinos (IBD)

Classification by final state

Background w/ true neutron

→ 2.2 MeV γ-ray emitted later
- ^{9}Li ★
- Atmospheric ν ★ (NCQE, $\bar{\nu}$ CC)
- Reactor ν

PMT dark noise,
radioactive in the wall, etc

Background w/o true neutron

→ low energy noise accidentally paired
- Spallation ★
- Atmospheric ν
- Solar ν